Computational toolkit for early-stage cost assessment and optimisation of BIPV façades

Tolga Özdemir

TU Delft

Presentation outline

- Introduction
- Foundation knowledge
- Case study (AMC Amsterdam)
- Design problem
- Computational design
- Conclusions

TU Delft

Introduction

- Half of the global population lives in urban settlements
- 75 per cent of the world's resources consumed by the urban residents.
- This necessitates the reduction of energy consumption and raising its generation.

Problem statement

- Buildings can generate their own energy with building integrated photovoltaic (BIPV) solutions and the application can be altered depending on the building context.
- BIPV not only pays off within a certain time frame, but also can finance other façade claddings such as green walls.
- However, the financial aspect of this type of technologies should be demonstrated and made clear to the investors.
- A tool for strengthening the communication between the designer and the investor is needed.

TUDelft

Main research question

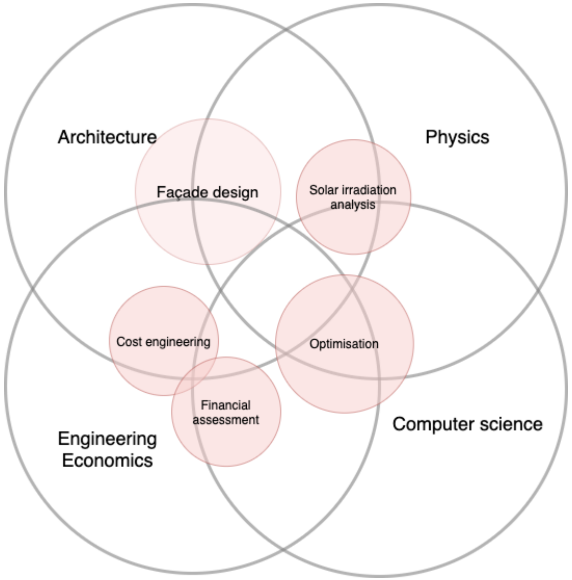
- How can the cost-effectivity of an early-stage BIPV design be assessed and optimised computationally within the frame of the AMC case?

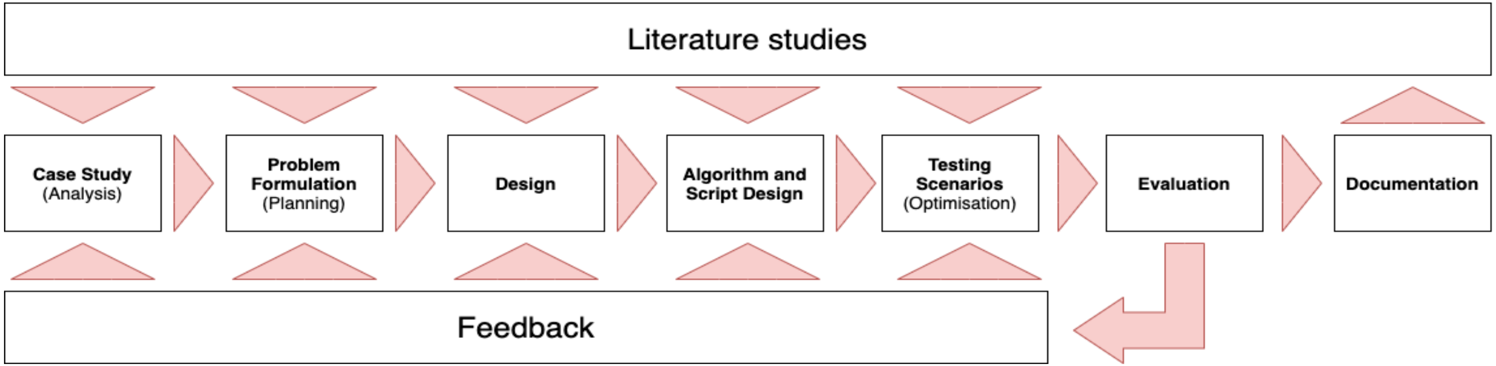
Research sub-questions

- Which measures can be taken to improve the energy performance of the AMC Amsterdam's external walls and what is the solar electricity potential of the building?
- Which façade systems can be used for BIPV retrofit to the AMC's concrete external walls, in combination with other cladding options?
- What may be the energy yield benefit compared to the added costs of custom-made BIPV-panels?
- What is the financial aspect of BIPV usage in combination with other façade materials, such as façades with vegetation?
- To what extent can the proposed computational design methodology maximise the profits on a limited budget?

TU Delft

Methodology

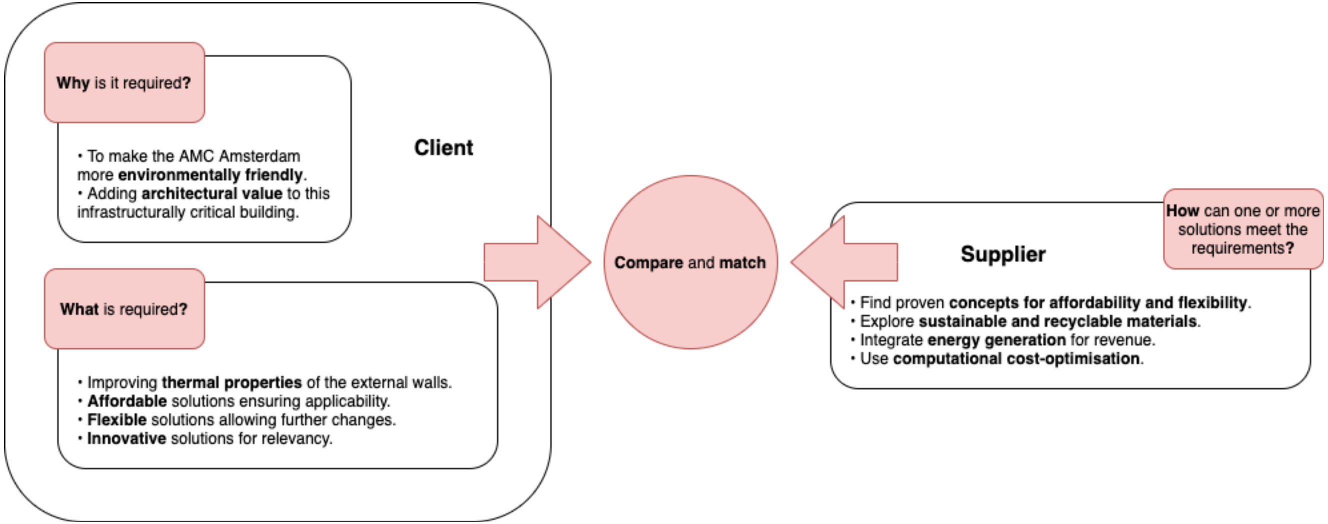




TU Delft

Foundation knowledge

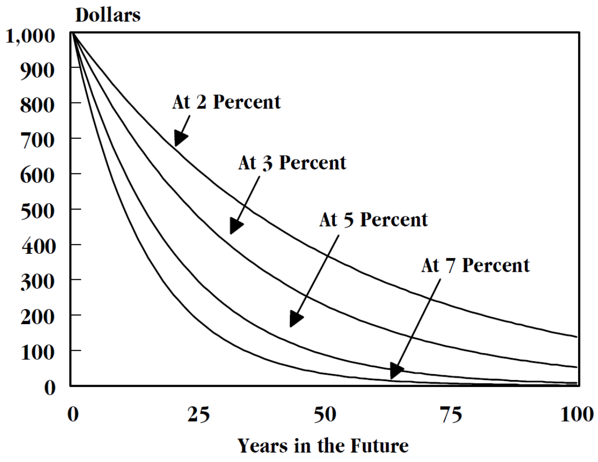
Performance approach



TU Delft

How to assess cost-effectivity

- **Time value of money (TVM):** The greater benefit of receiving money now rather than an identical sum later.



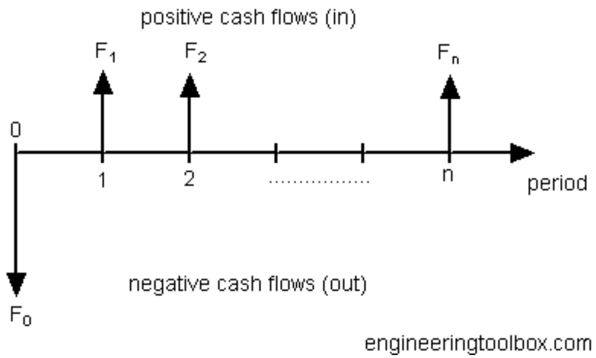
- $FV = PV \times [1 + i]^t$

FV	Future value of money
PV	Present value of money
i	interest rate
t	number of years

(Newnan et al., 2004)

How to assess cost-effectivity

- **Net present value (NPV):** is a method used to determine the current value of all future cash flows generated by a project.



- $$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

Rt	Net cash flow in period t
i	interest rate
t	number of years

(Mao, 2006)

How to assess cost-effectivity

- **Net present value (NPV)**

NPV<0	No investment
NPV=0	Goodwill is determinant
NPV>0	Pursue the project

How to assess cost-effectivity

- **Levelized cost of electricity (LCoE):** is a measure of the average net present cost of electricity generation for a power plant over its lifetime.

- $LCoE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime}$

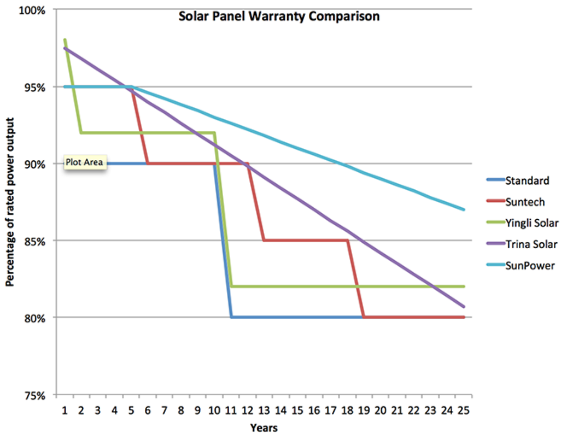
$$= \frac{\sum_{t=1}^{n} \frac{I_t}{\cdots} \cdots}{\sum_{t=1}^{n} \cdots}$$

n	the lifetime of the system
I_t	investment expenditures in the year t
M_t	operational expenditures in the year t
F_t	fuel expenditures in the year t
E_t	the electrical energy produced in the year t
r	discount rate

(Smets et al., 2016)

PV technology

- **Calculation uncertainty**
- 9,7 per cent
- PV-cell degradation

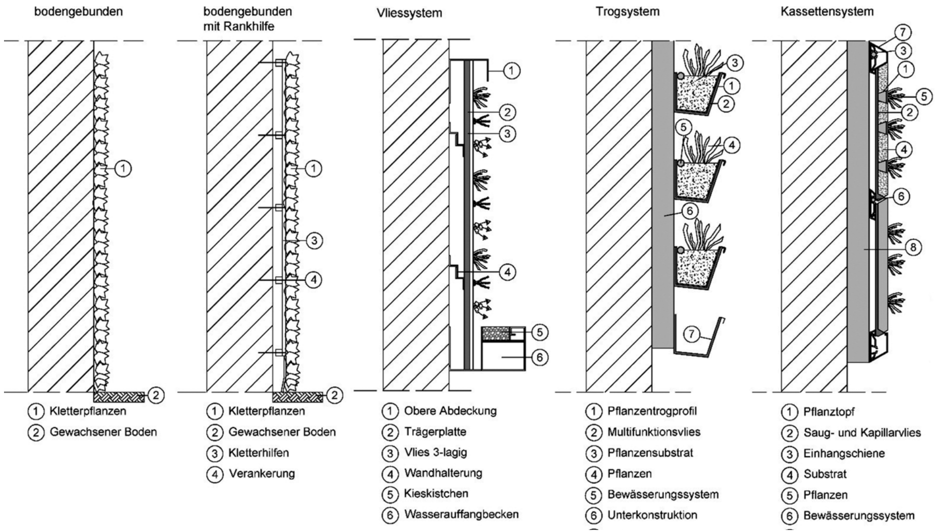


https://energyinformative.org/lifespan-solar-panels/

Group	Uncertainty
Solar resource	Climate models (4%) Solar insolation variability (5%) Transposition to the plane-of-array (3%)
PV modelling	Module rating (3%) PV cell degradation Shading Snow, dirt and soiling (3,5%) Other (temperature rise, spectral losses, reflection etc.) (5%)
Other field related uncertainties	Inverter and transformer losses (1%) AC and DC cabling

(Richter et al., 2015; Thevenard & Pelland, 2013)

Façades with vegetation



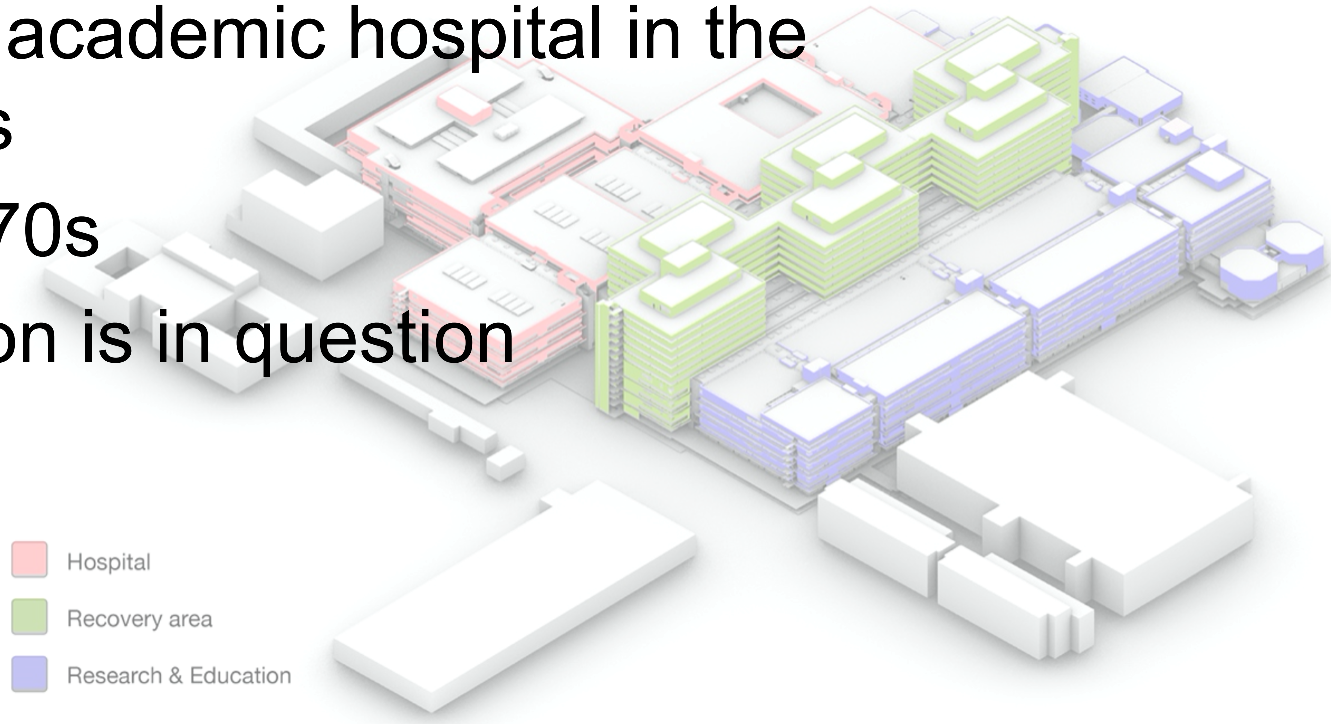
(Hollands & Korjenic, 2019)

- Many studies showed the positive effect of the nature views on people's health (Kaplan, 1995; Ulrich, 1984) .
- In a hospital context this would add value to the building.
- Thermal benefits
- Environmental benefits (urban heat island effect, noise reduction, biodiversity etc.)

Case study: AMC Amsterdam

AMC Amsterdam

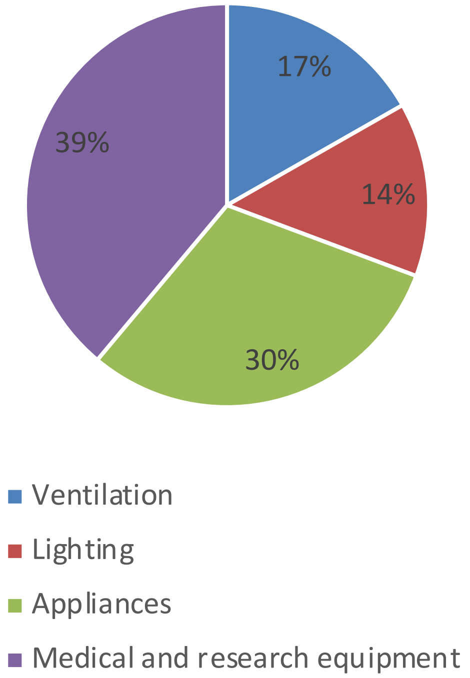
- The largest academic hospital in the Netherlands
- Built in the 70s
- Its renovation is in question



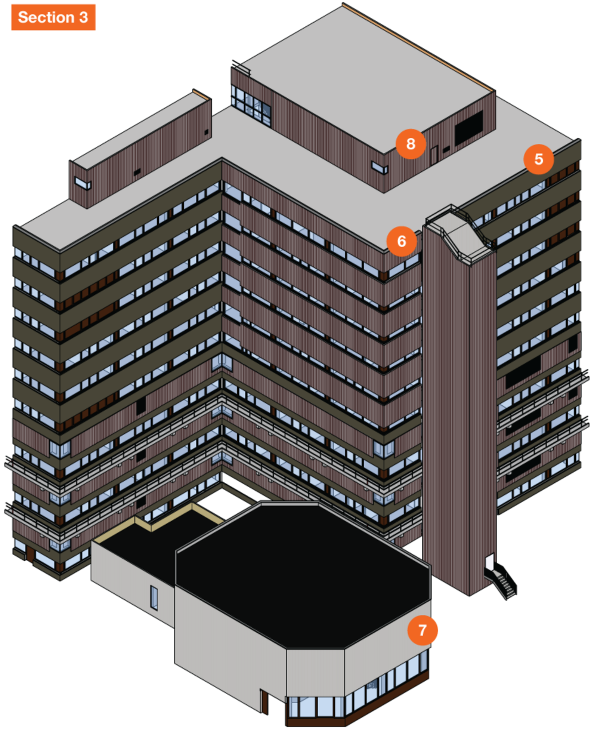
TU Delft

AMC energy usage

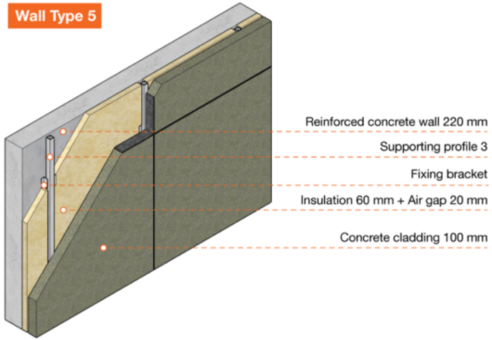
- Total of 125.334 MWh/year
- 90% self-production (CHP plant)
- 10% purchase from the grid

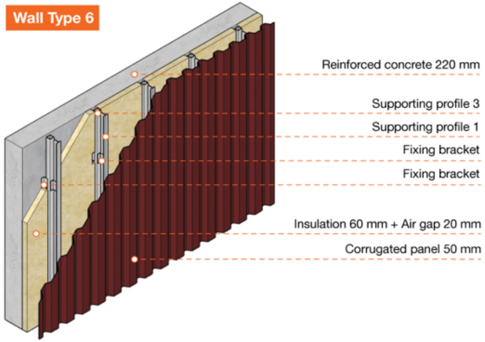


Façade types



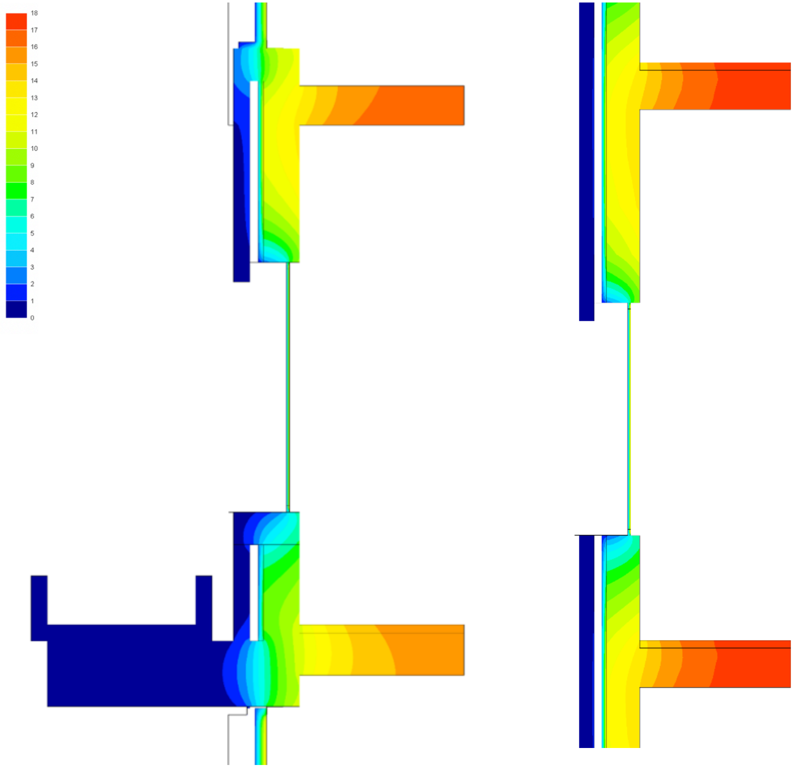
- Low-rise and high-rise buildings where the offices and the patient rooms are located
- Priority regarding thermal improvement
- Concrete wall core





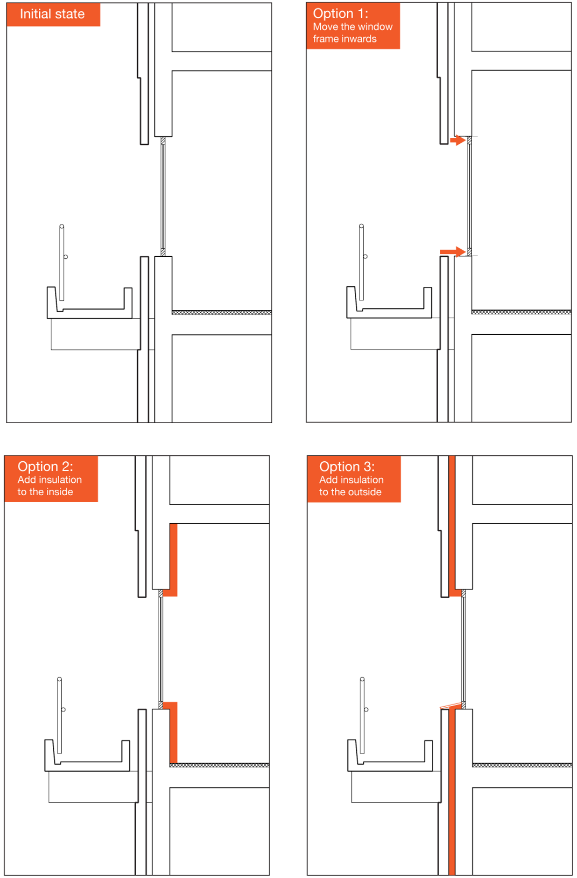
TU Delft

Façade thermal properties



- Low-rise and high-rise buildings
- The ageing of materials results in lower insulation value.
- The concrete strip on the façade loses much heat due to thermal bridges.
- Rc;l=0,56 m^2K/W and Rc;h=0,61 m^2K/W
- (DGMR Bouw, 2016)
- Dutch Building Decree 2012
- Rc;new= 4,50 m^2K/W and Rc;renew= +1,30 m^2K/W

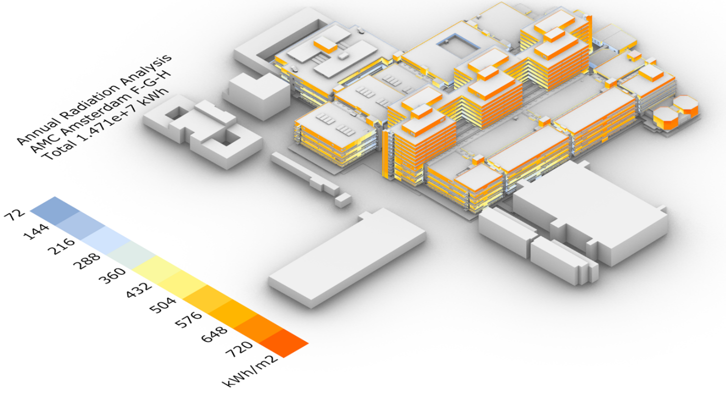
TU Delft

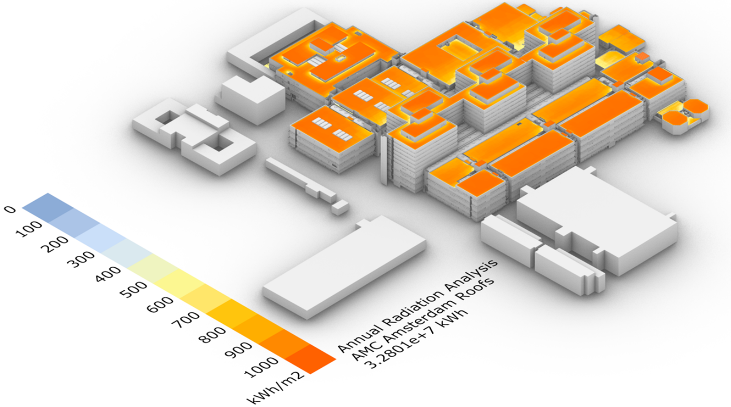


Façade thermal improvement

- If there is a well-ventilated layer of air in construction, Rc value can be calculated by counting only the specific heat resistances of the layers that are situated on the inside of the air layer (van der Linden, 2013)
- $R_c = R_1 + R_2 + R_3 + \cdots$
- 180 mm exterior insulation
- 120 mm total insulation if interior is insulated and covered with gypsum board and plaster
- Tilting angle was limited, due to clashing with the balconies and daylight issues

TU Delft





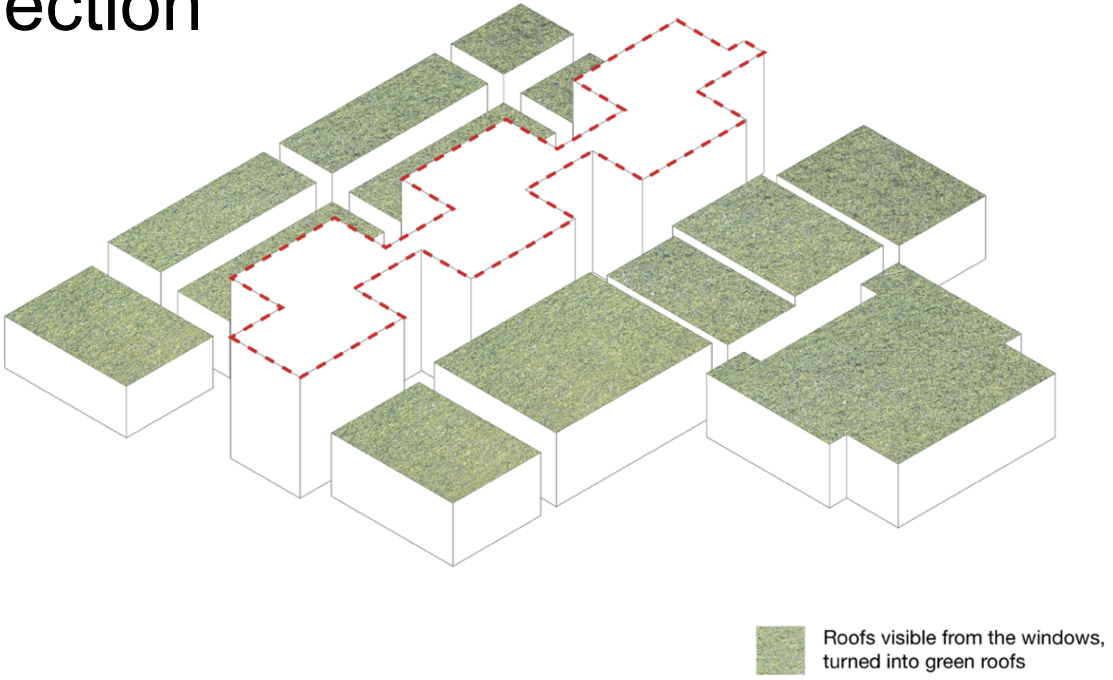
Solar electricity potential

- Annual consuption is **125.334 MWh**
- **Façade-balcony**
- Area 48.869 m²
- Insolation 14.710 MWh
- **1.977 MWh*** energy generation (1,5 per cent)
- **Roof**
- Area 40.429 m²
- Insolation 32.800 MWh (3,5 per cent)
- **4.408 MWh*** energy generation
- *with 0,16 panel efficieny and 0,84 performance ratio

TU Delft

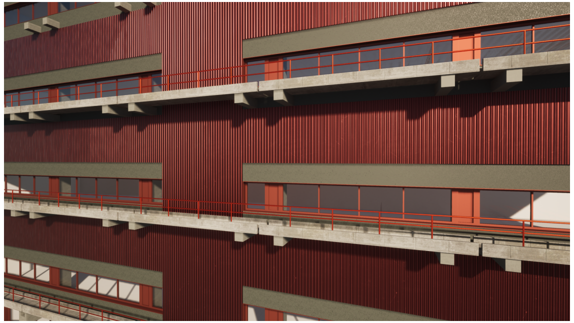
Energy vs. water collection in the roofs

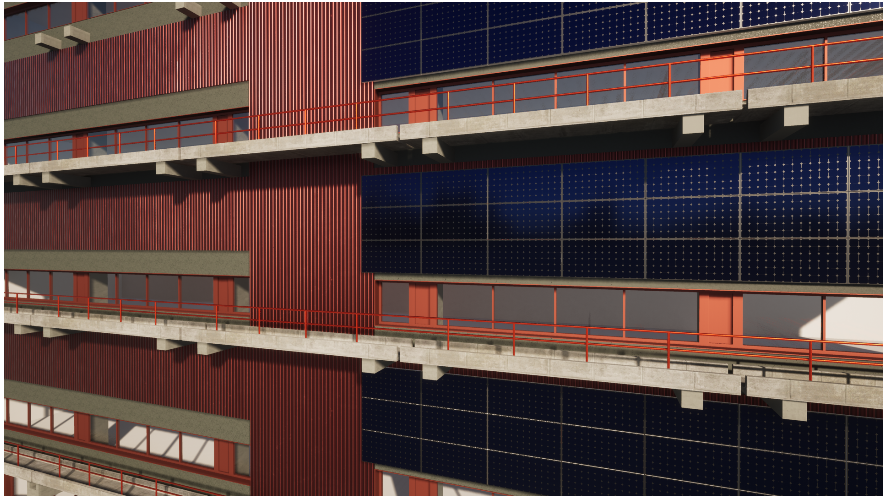
- Rainwater collection
- Green views

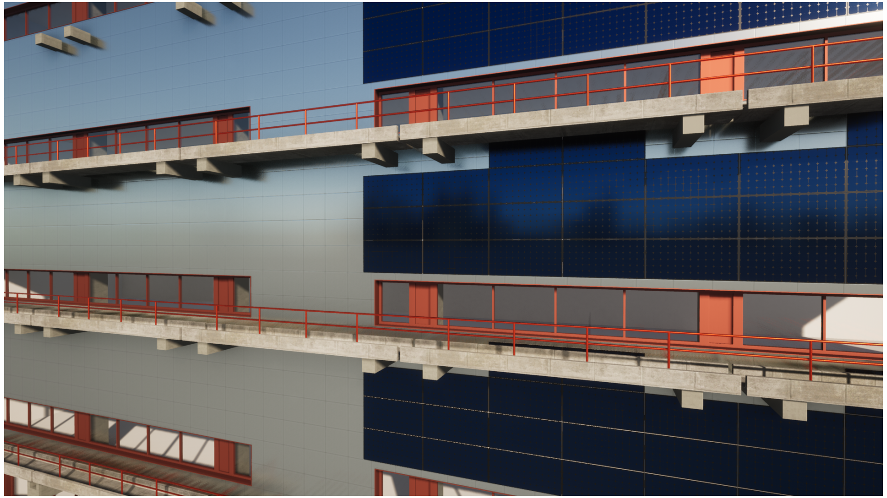


PV façade

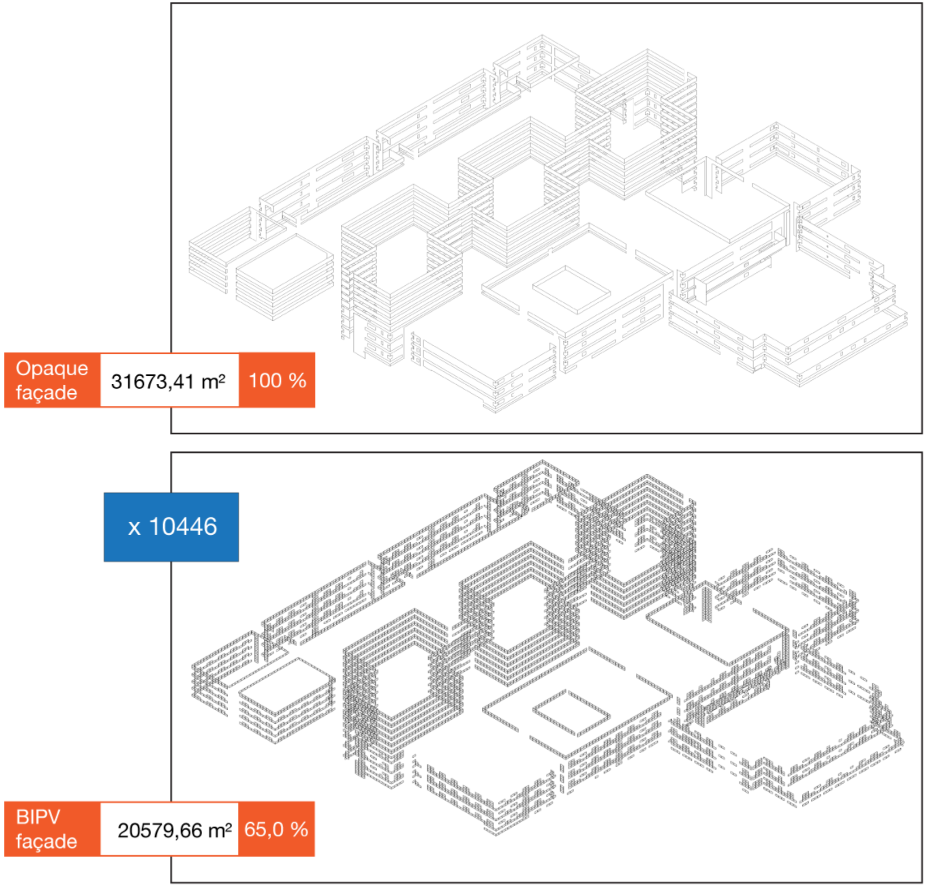
- Building-applied photovoltaics (BAPV) or
- Building-integrated photovoltaics (BIPV)







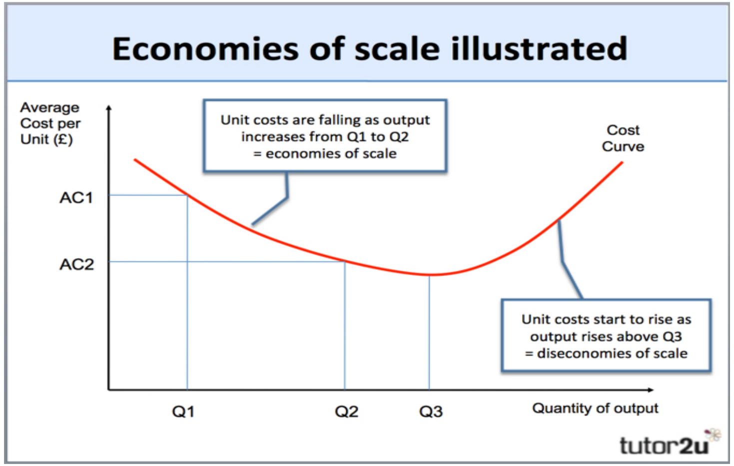
Commercial PV-modules



- 72-cell commercial PV modules
- 199 cm by 99 cm
- 65 per cent of the façade covered

TU Delft

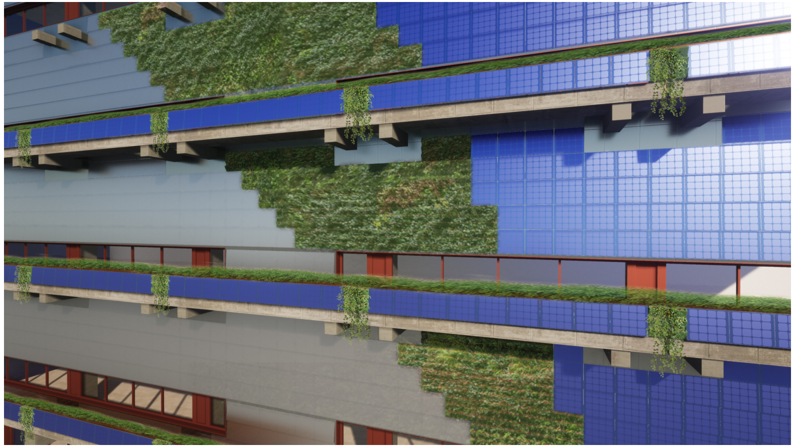
Design challenges

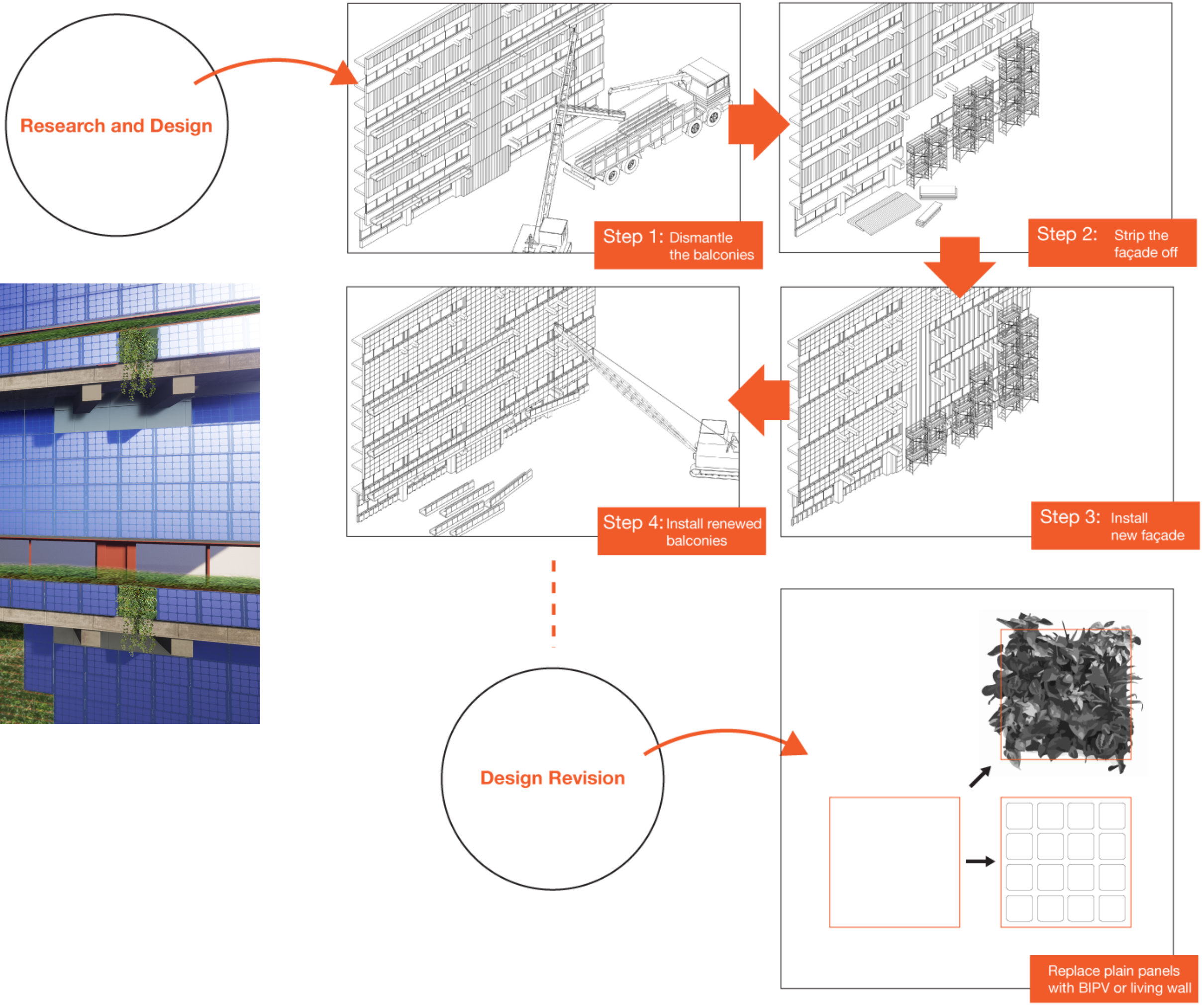


- Modular and flexible façade system to adapt to the changing needs of the building
- Increase the coverage percentage (65 per cent) for more energy generation
- Use as many of the identical panels as possible (economies of scale)

TU Delft

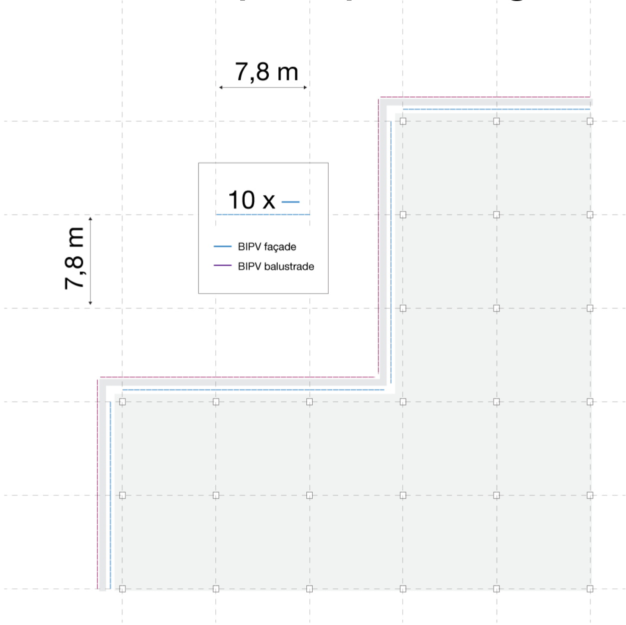
Project vision

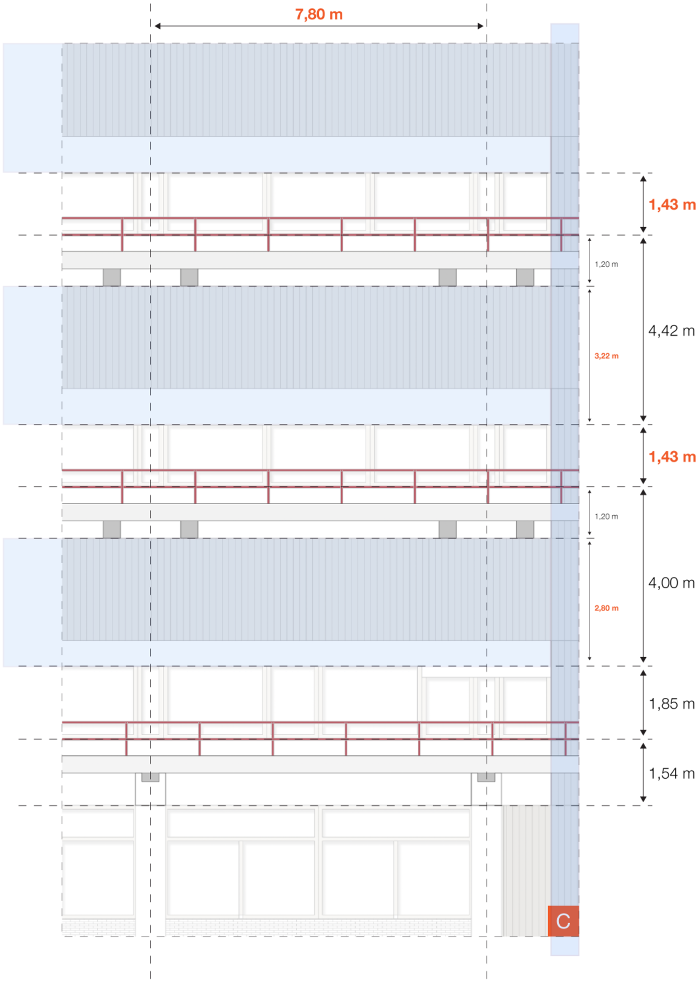




Building dimensions

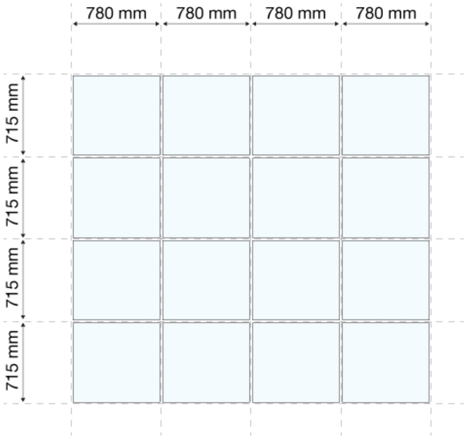
- 7,8 m between 2 consecutive columns
- 1,43 m window and parapet height



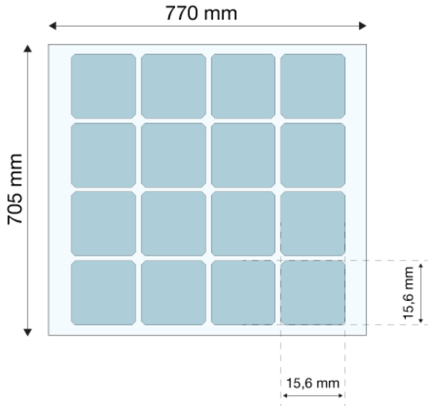


Panel dimensions

- 780 mm by 715 mm grid
- 10 mm gap between panels
- 770 mm by 705 mm panels
- 16 c-Si cells per PV-module

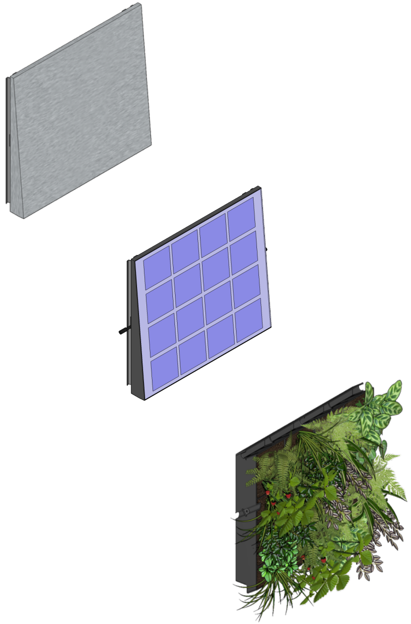


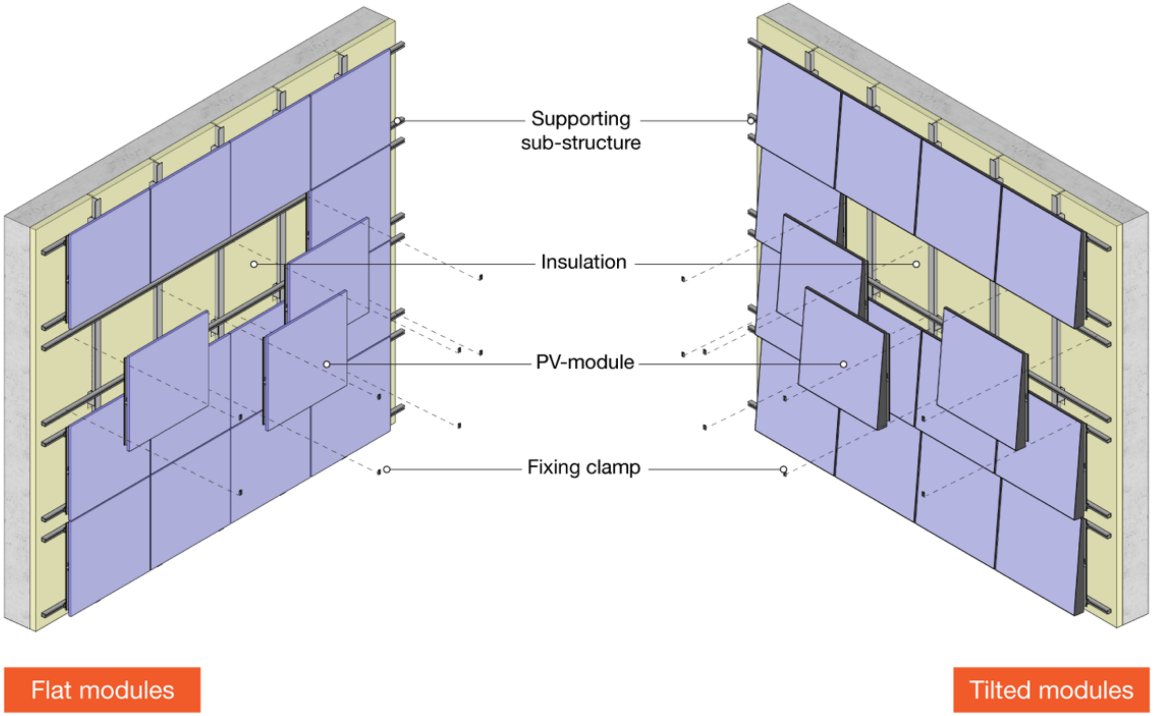
Façade layout



PV-module layout

Façade design

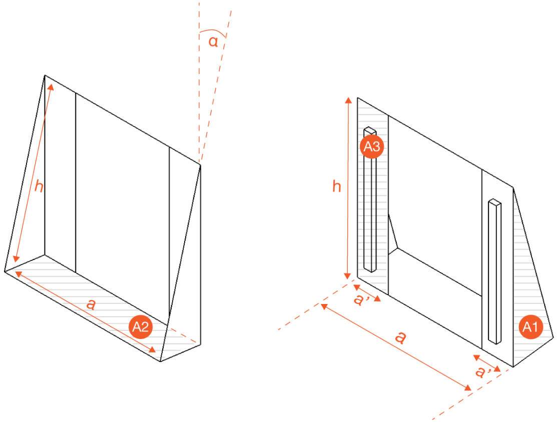


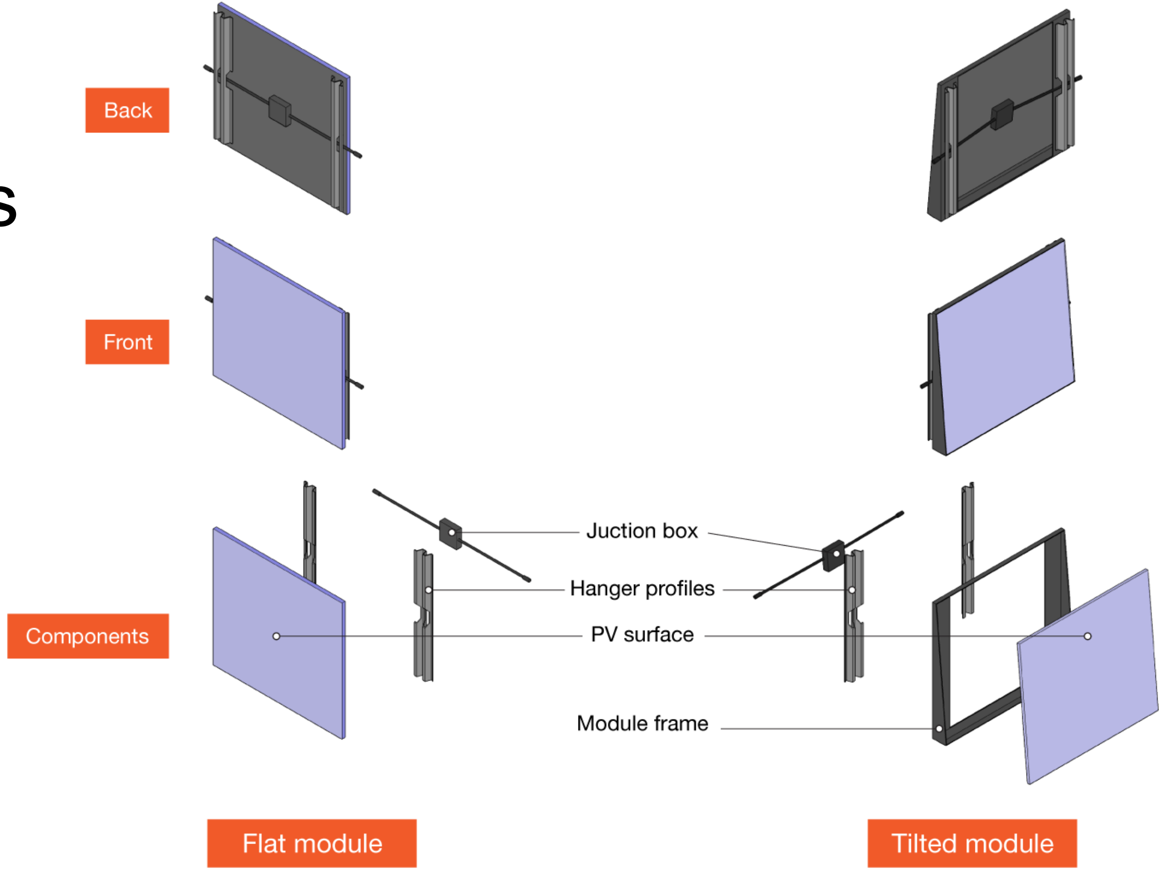


- Interchangeable modules

Panel design

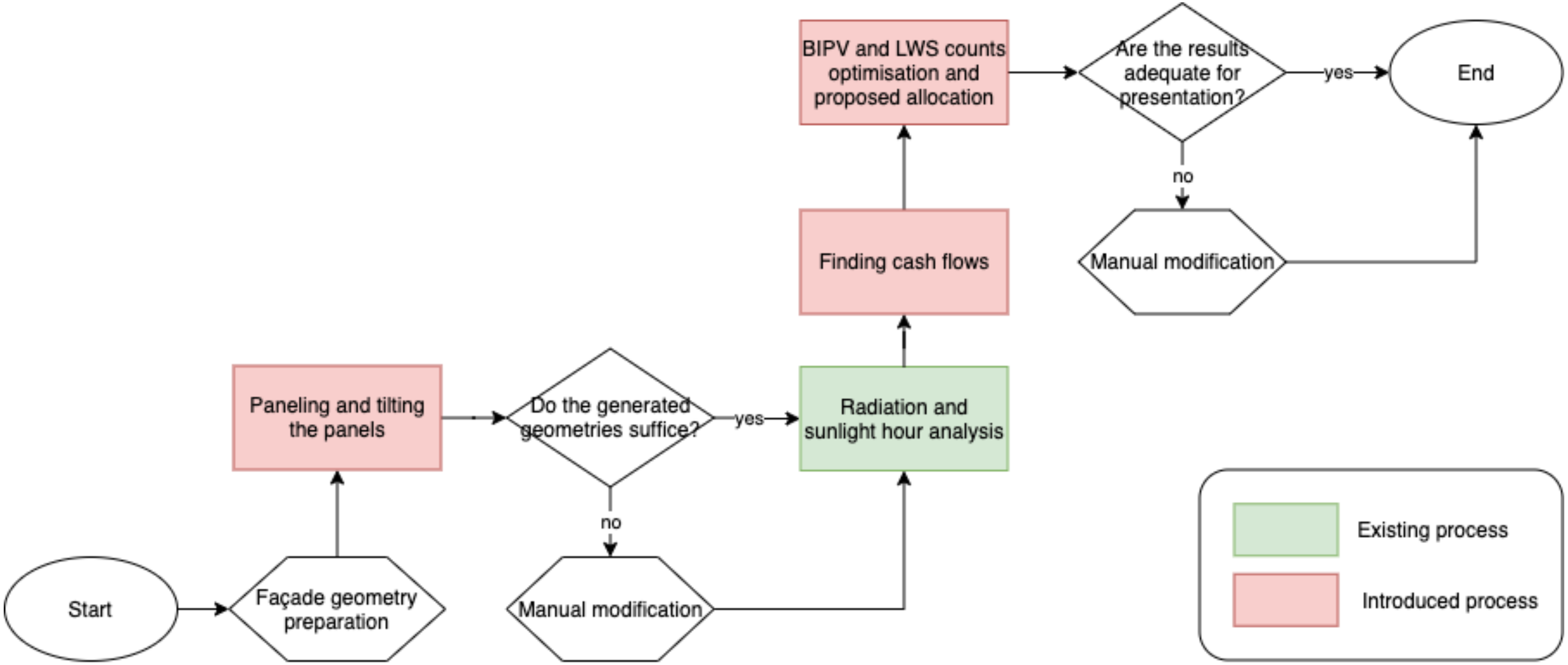
- Cost calculations
- Depends on the supplier



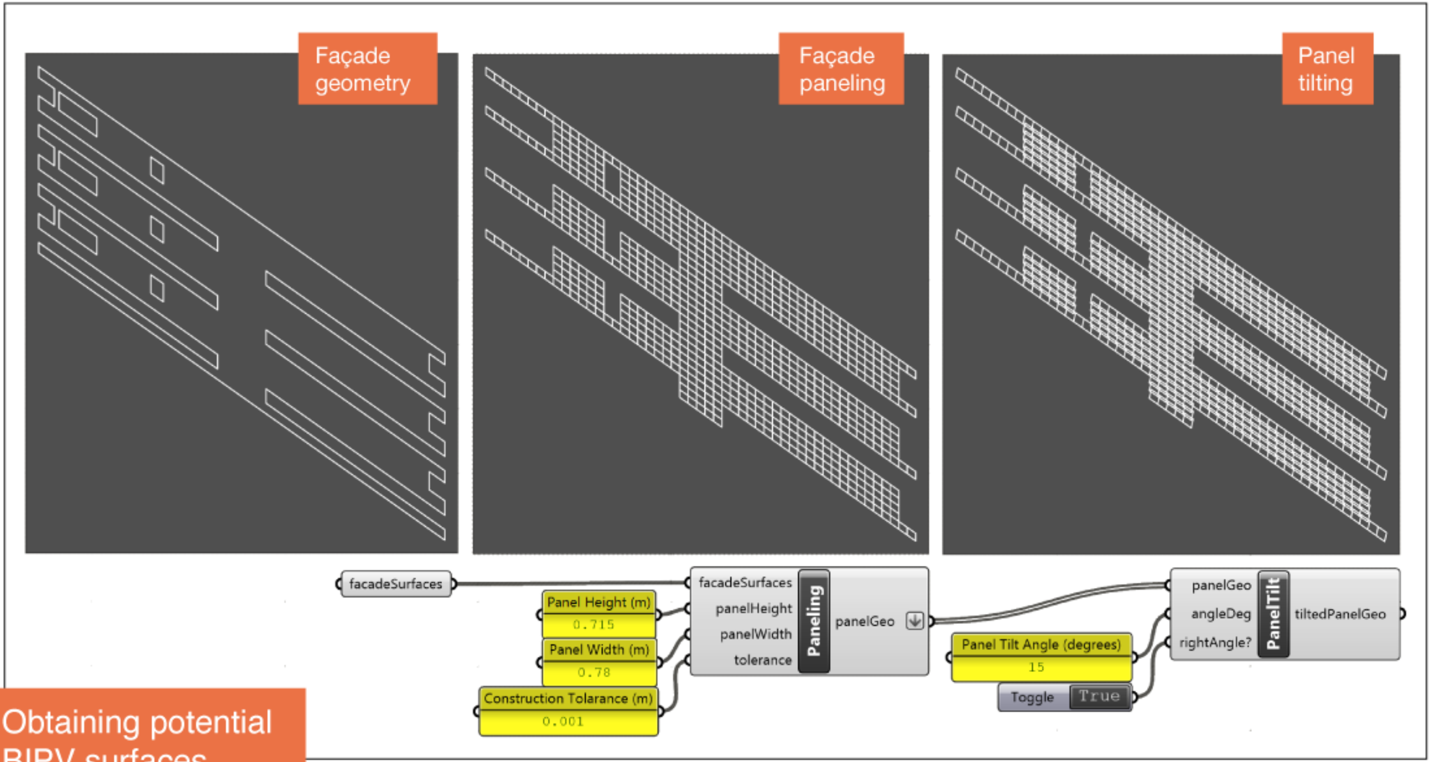


TU Delft

Computational workflow

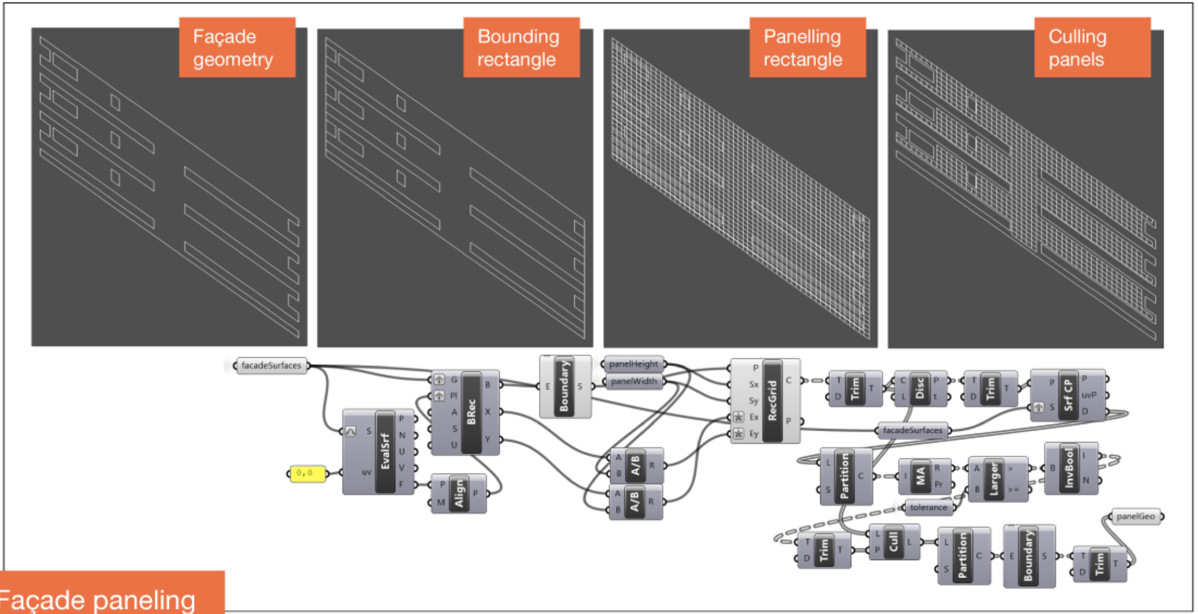


Toolkit: Panel geometry

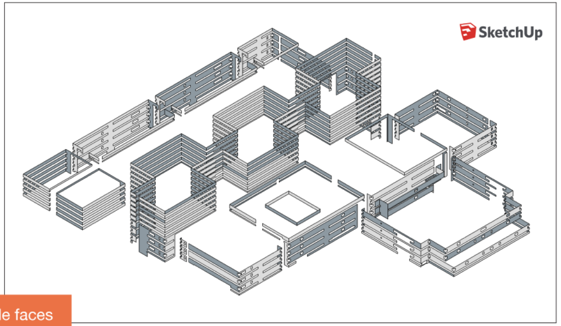


Obtaining potential BIPV surfaces

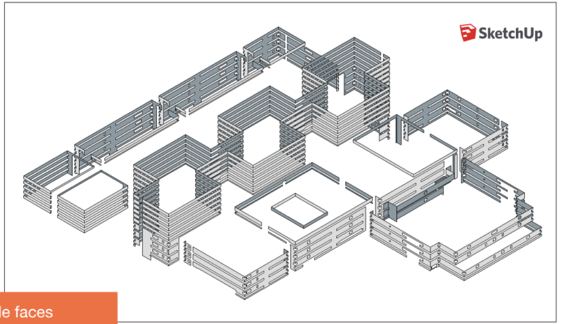
Façade panelling



Façade paneling



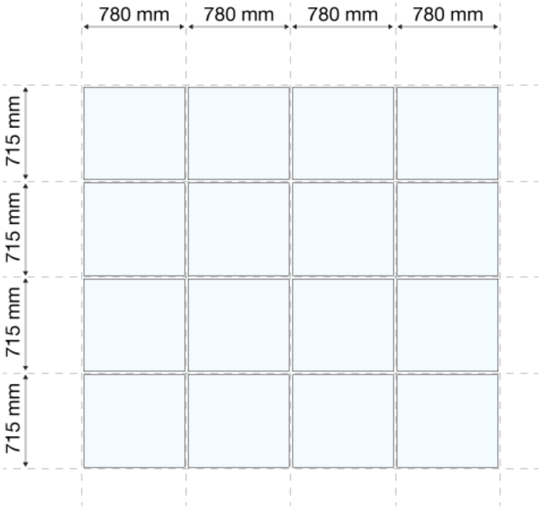
Façade faces not aligned

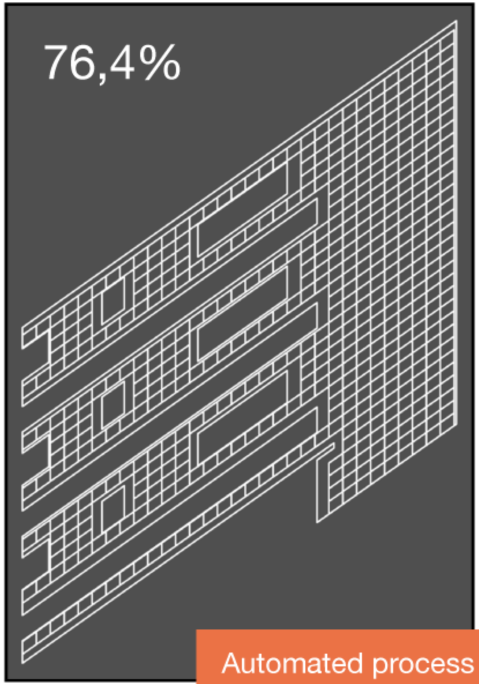


Façade faces aligned and oriented

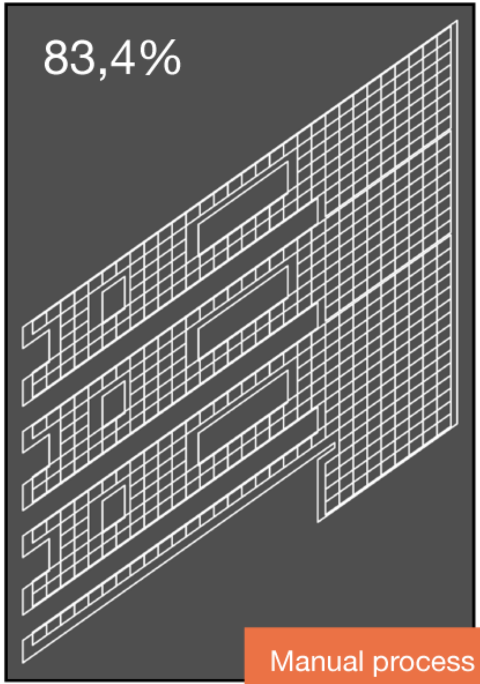
TU Delft

Façade panelling (automated vs. manual)





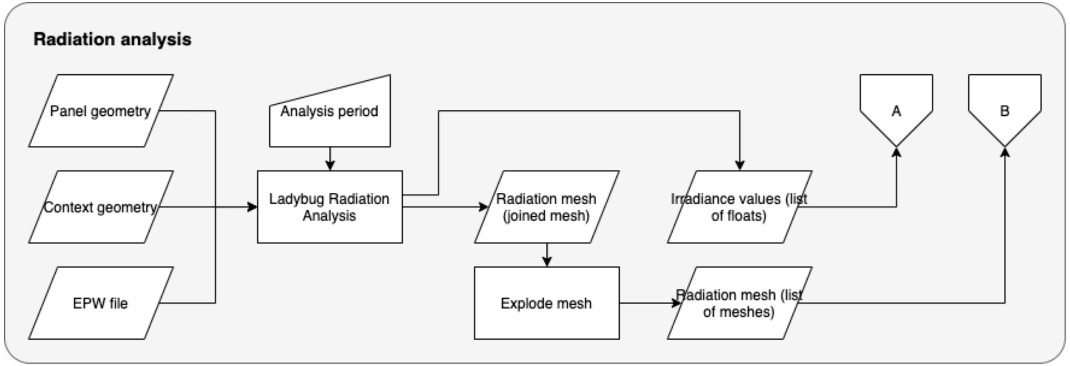
Automated process
512 panels

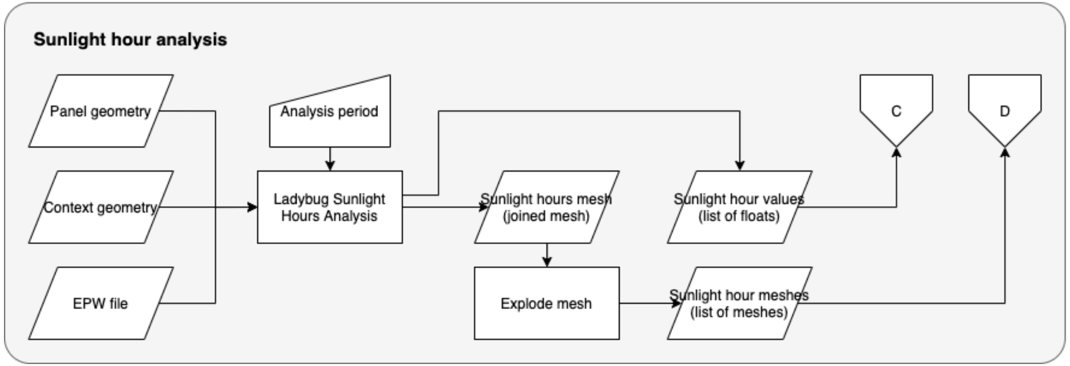


Manual process
559 panels

Solar analyses

- Radiation analysis for electricity generation
- Sunlight hour analysis for LWS.

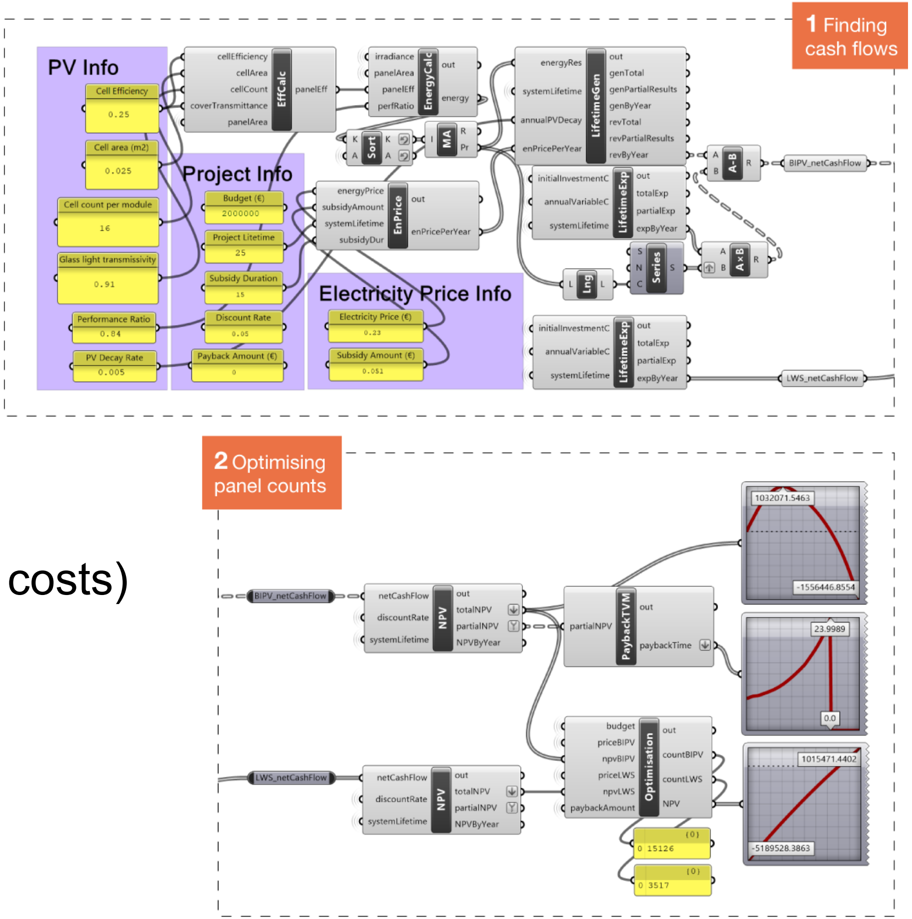




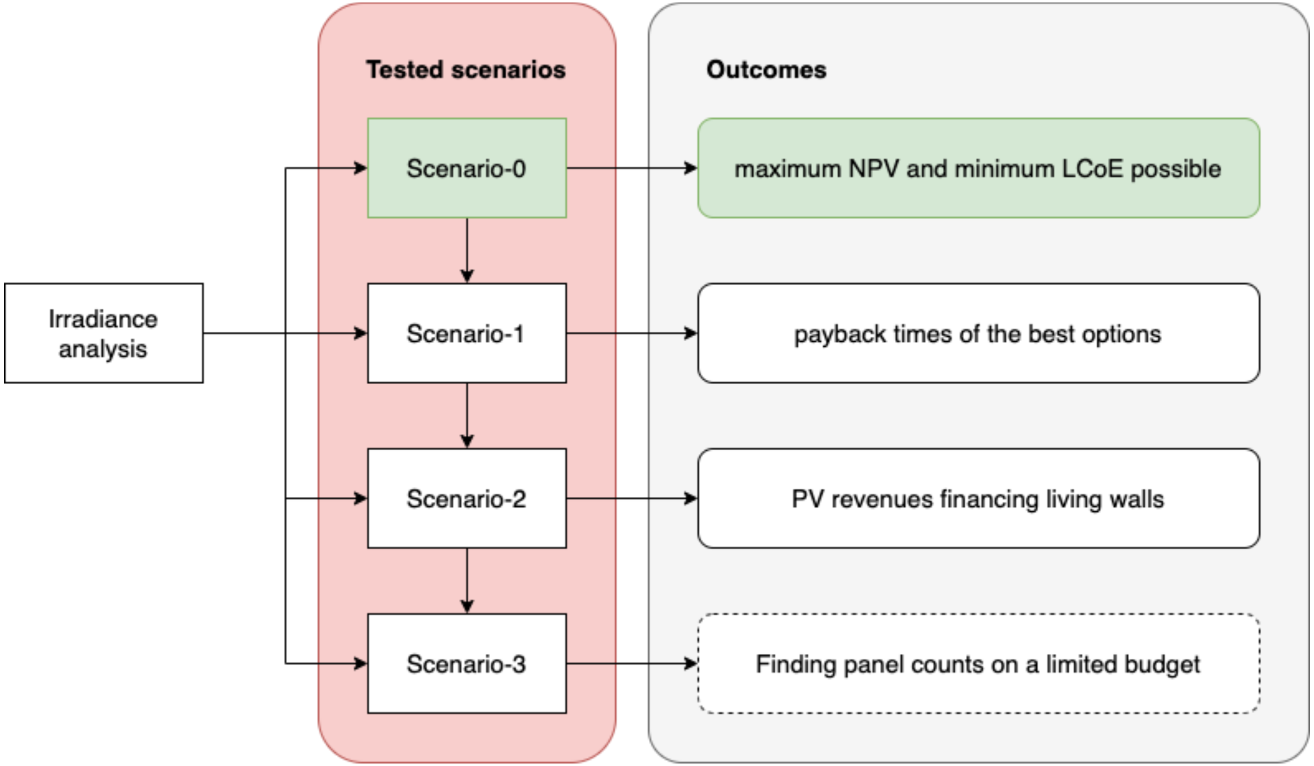
Toolkit: Cash flows and optimisation

Calculators:

- Panel efficiency
- Energy yield (performance ratio)
- Energy selling price (subsidies)
- Lifetime energy generation (PV decay)
- Lifetime expenditures (initial and annual costs)
- NPV
- LCoE
- Payback time
- Iterative optimiser

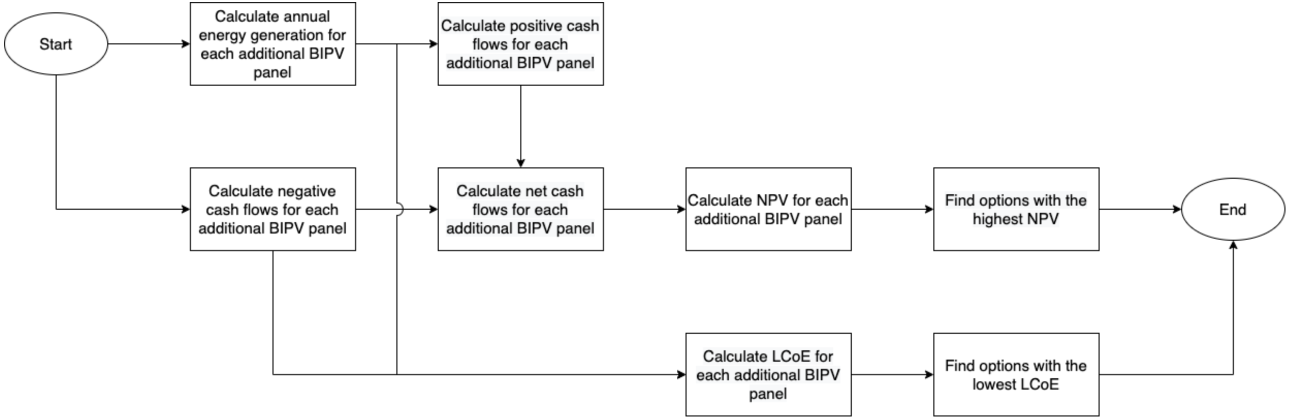


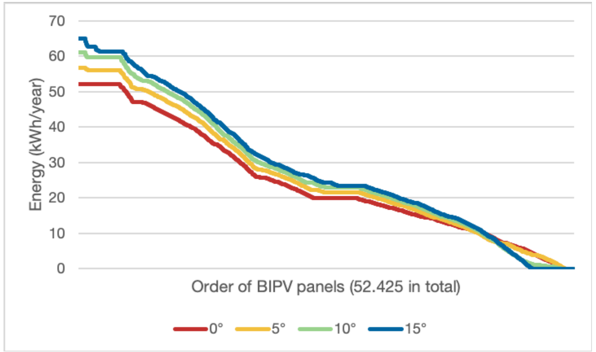
Learning from scenarios

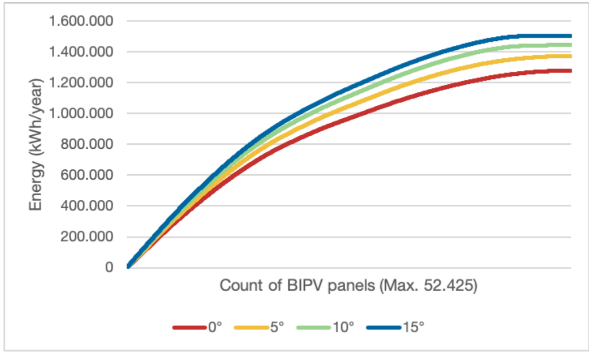


TU Delft

Scenario-0: NPV and LCoE

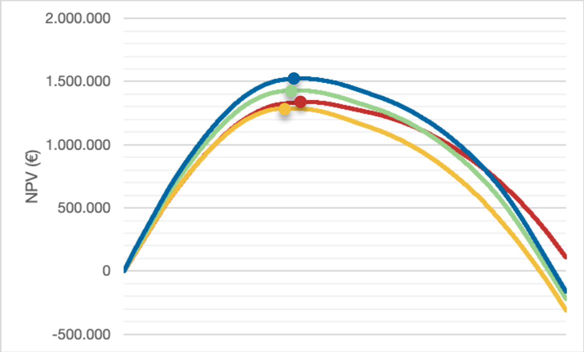




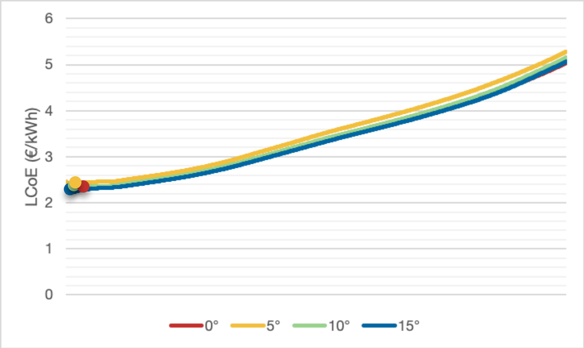


TU Delft

Scenario-0 results



	0°	5°	10°	15°
Count of panels	21.764	19.519	20.620	20.800
Total price (EUR)	1,21M	1,39M	1,54M	1,63M
Max. NPV25 (EUR)	1,34M	1,29M	1.43M	1,53M

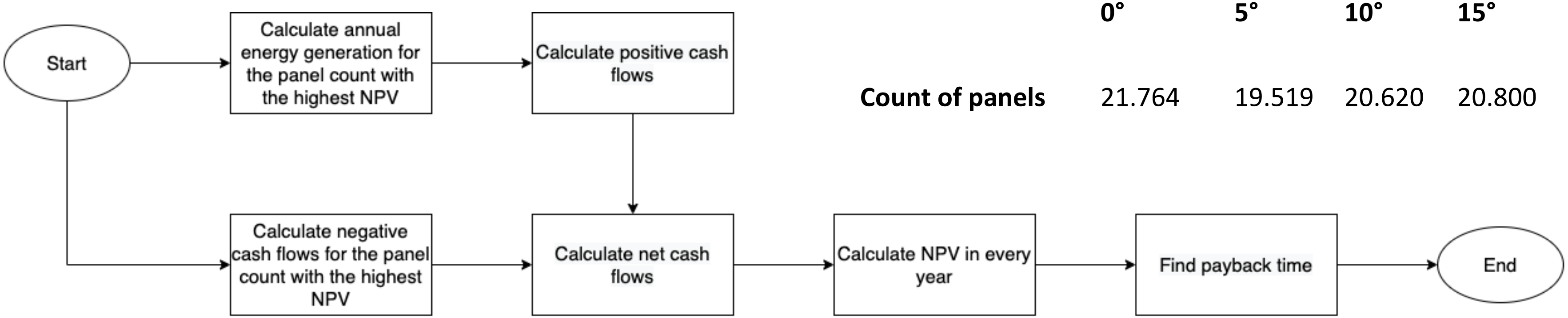


	0°	5°	10°	15°
Count of panels	3627	675	143	75
Total price (EUR)	201K	48K	10K	6K
Min. LCoE25 (EUR/kWh)	2,35	2,43	2,32	2,24

PV LCoE for the Netherlands is EUR 0,12/kWh for 2015 (Statista, 2016)

TU Delft

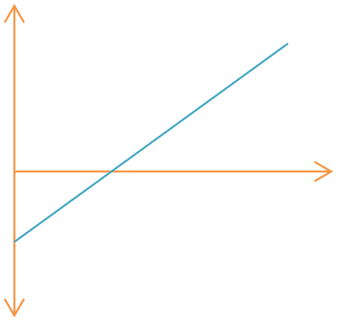
Scenario-1: Payback time

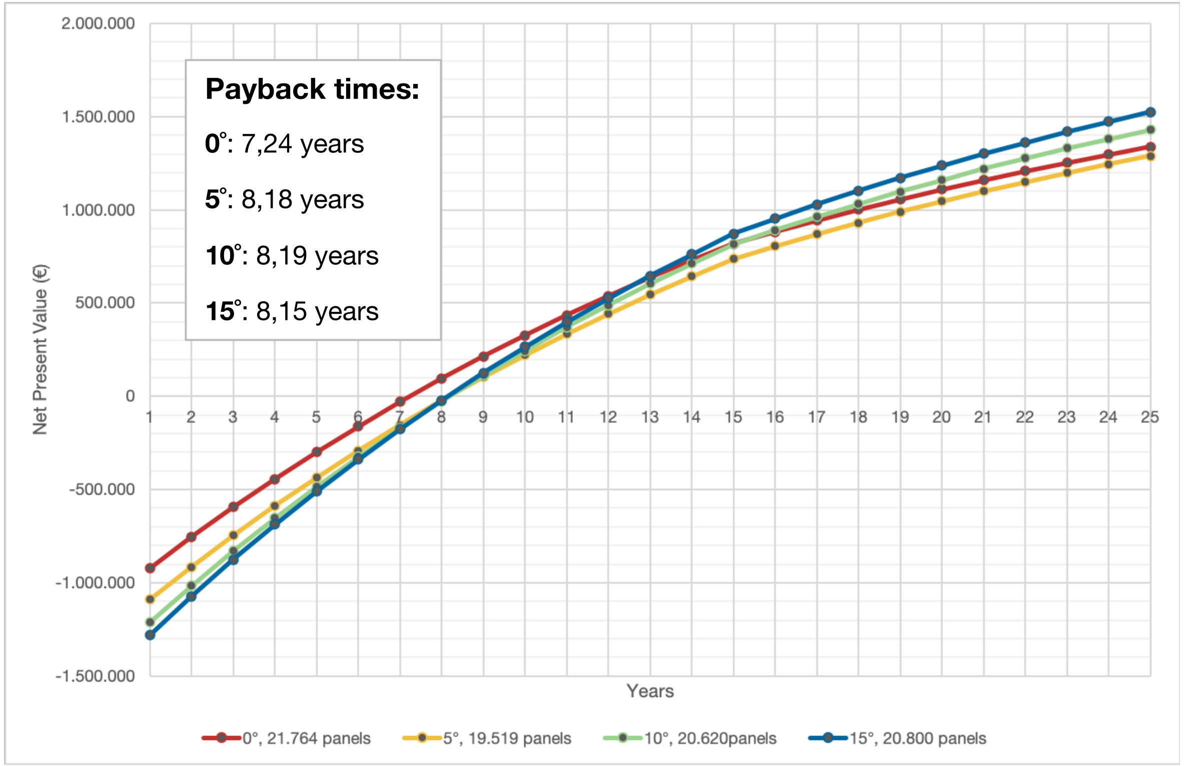


	0°	5°	10°	15°
Count of panels	21.764	19.519	20.620	20.800

Scenario-1 results

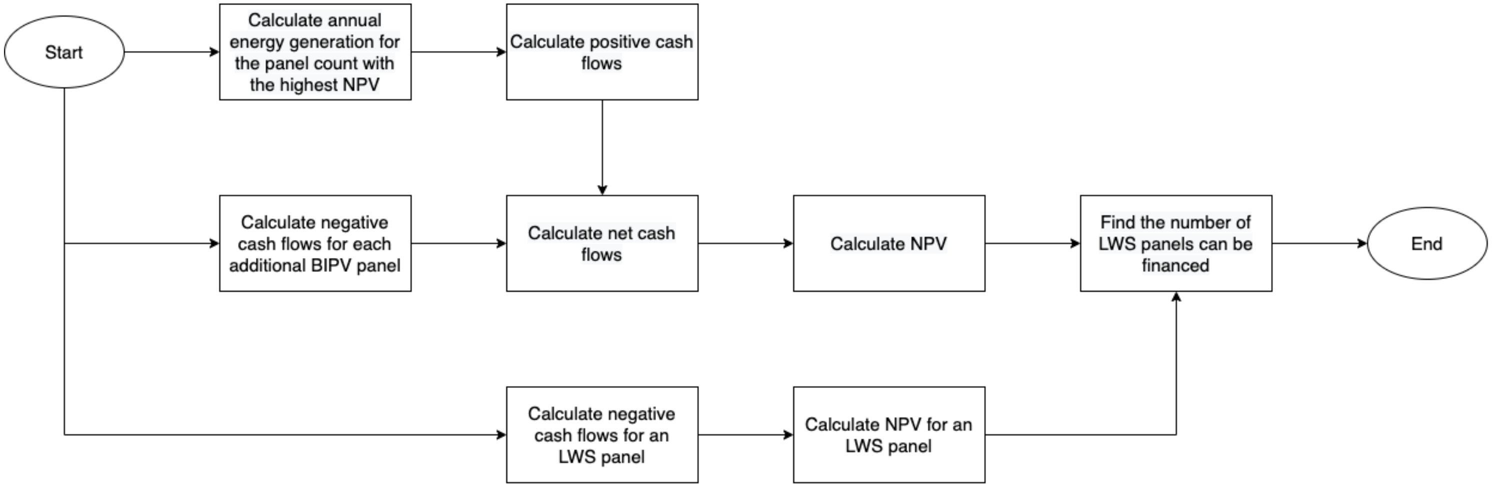
$$payback\ time = \frac{initial\ investment}{annual\ return}$$



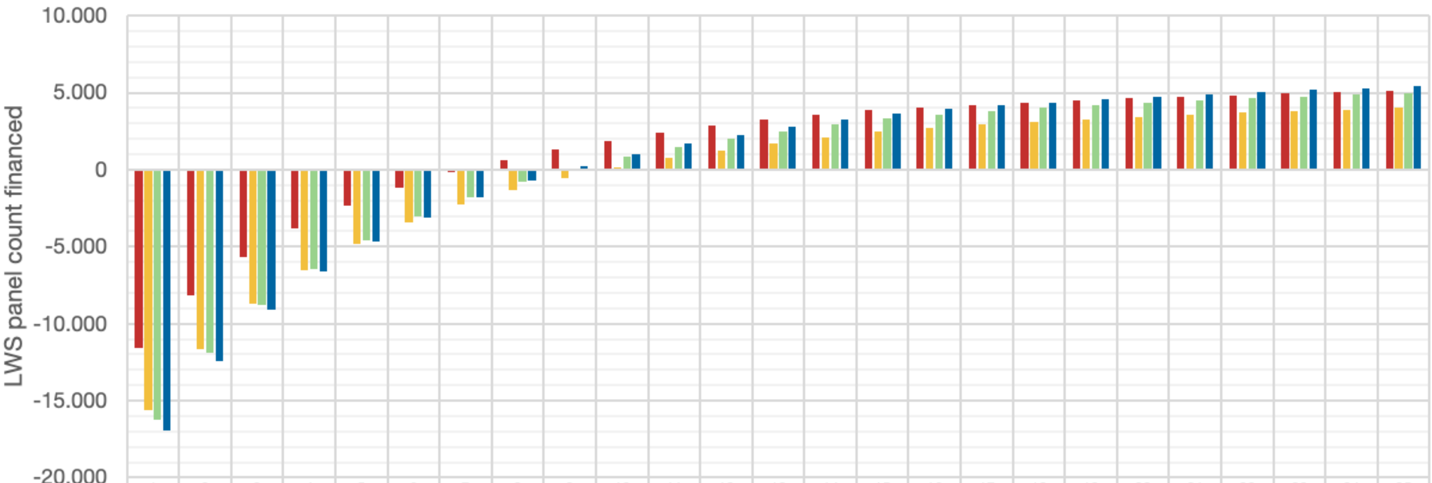


TU Delft

Scenario-2: Financing LWS



Scenario-2 results

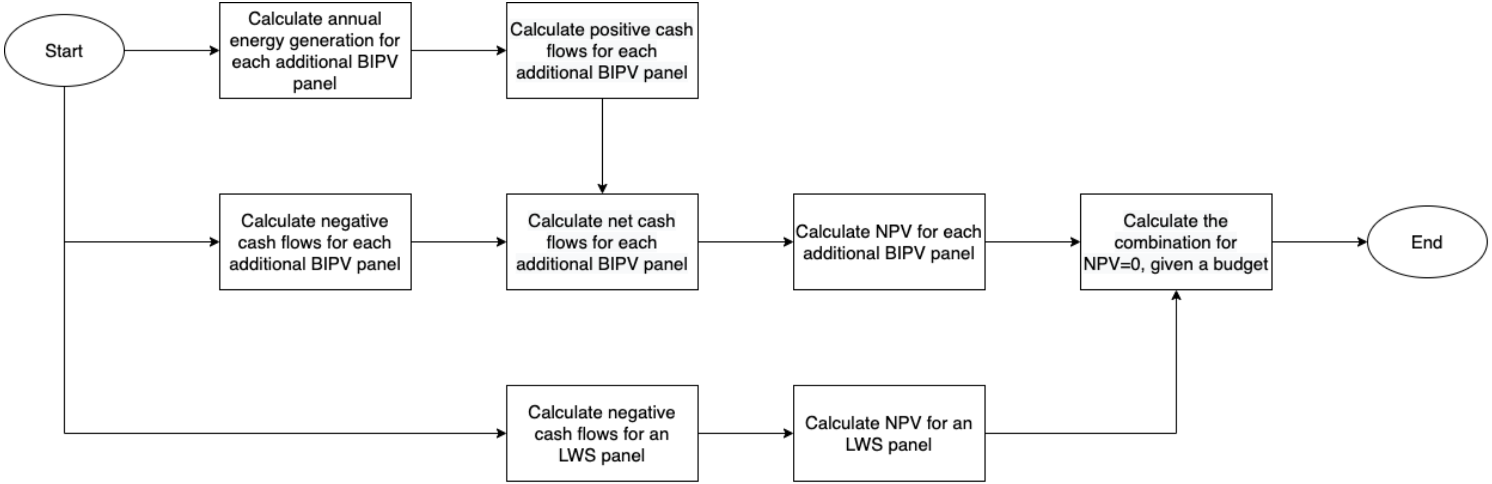


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
0°	-11576	-8175	-5703	-3827	-2355	-1172	-201	610	1296	1883	2391	2834	3224	3569	3876	4057	4220	4367	4500	4622	4732	4833	4926	5012	5090
5°	-15603	-11622	-8728	-6532	-4810	-3424	-2287	-1339	-536	152	747	1266	1722	2126	2486	2712	2916	3101	3268	3420	3558	3685	3801	3908	4007
10°	-16232	-11927	-8796	-6420	-4557	-3059	-1829	-803	66	809	1453	2014	2508	2945	3333	3577	3797	3995	4174	4337	4486	4623	4748	4863	4969
15°	-16975	-12433	-9130	-6624	-4659	-3078	-1781	-698	218	1003	1682	2274	2794	3255	3665	3923	4155	4364	4554	4727	4884	5028	5160	5282	5394

Project lifetime (years)

0° 5° 10° 15°

Scenario-3: Optimisation



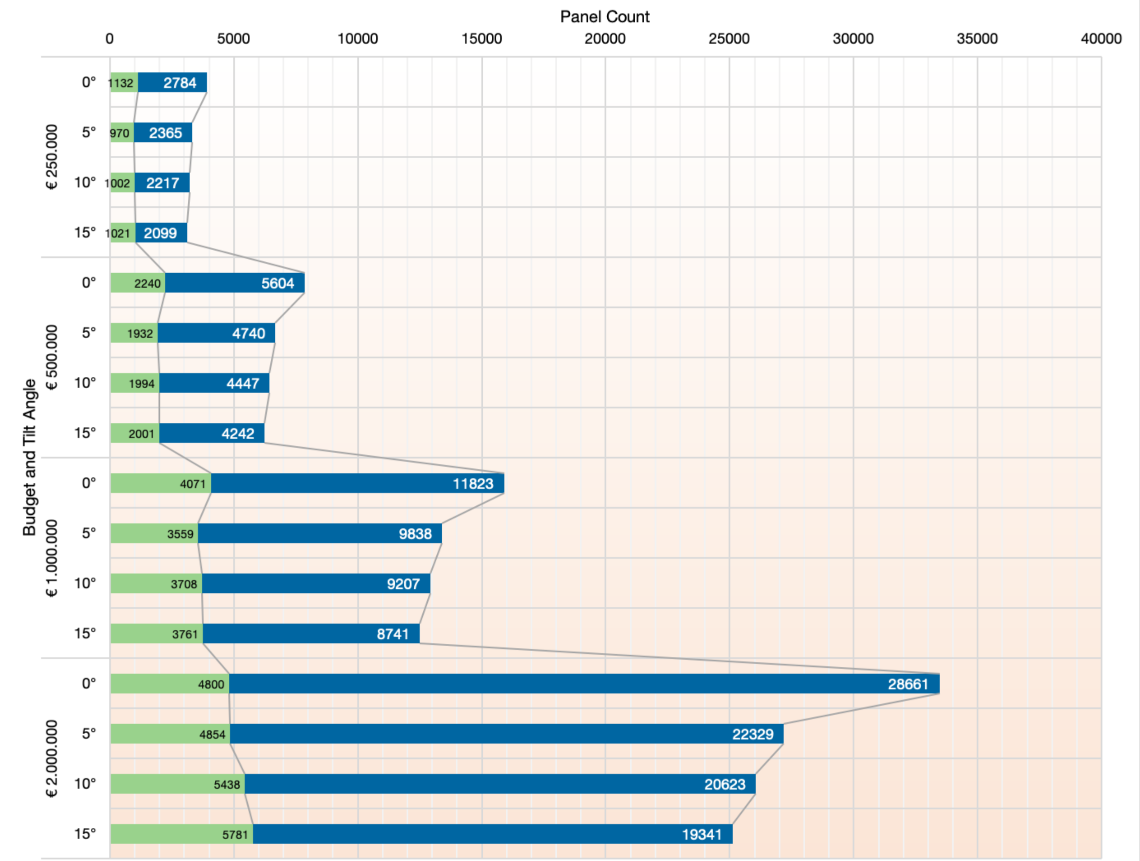
Panel counts

Tested budgets:

- €250.000
- €500.000
- €1.000.000
- €2.000.000

Tilt angles:

0°, 5°, 10°, 15°

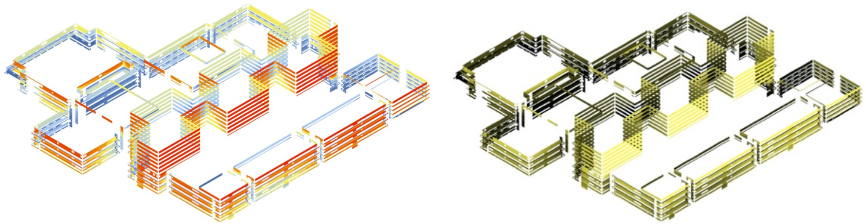


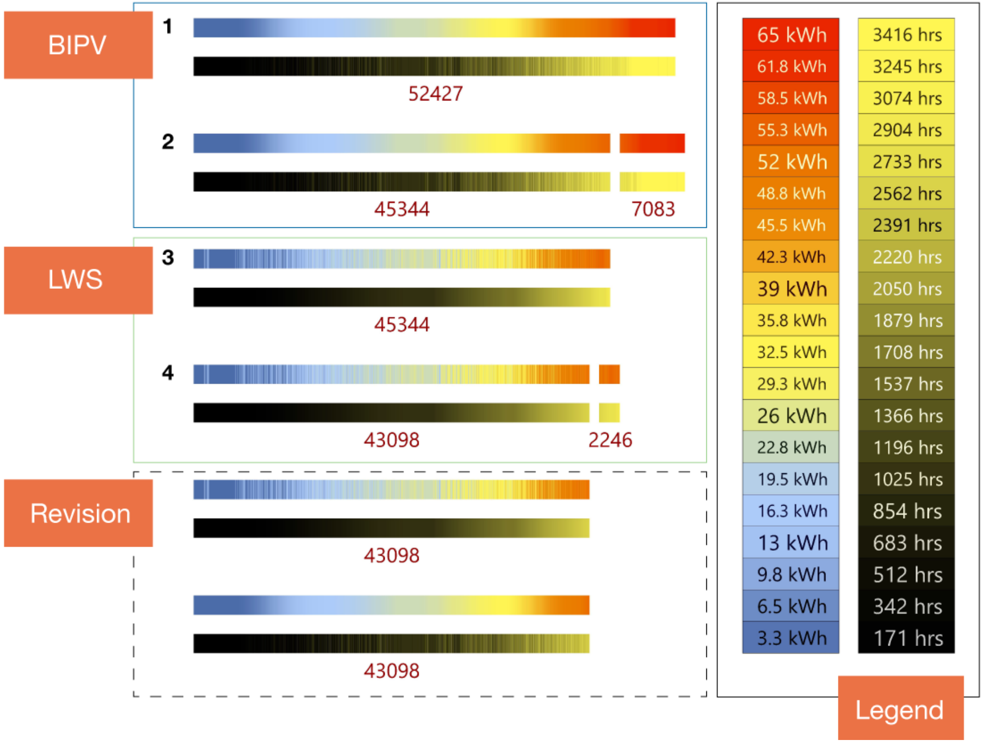
	€ 2.000.000				€ 1.000.000				€ 500.000				€ 250.000			
	15°	10°	5°	0°	15°	10°	5°	0°	15°	10°	5°	0°	15°	10°	5°	0°
LWS	5781	5438	4854	4800	3761	3708	3559	4071	2001	1994	1932	2240	1021	1002	970	1132
BIPV	19341	20623	22329	28661	8741	9207	9838	11823	4242	4447	4740	5604	2099	2217	2365	2784

TUDelft

Panel allocation

1. Sorting the panels by their radiation values.
2. Reserving the best places for BIPV to maximise energy generation.
3. Sorting remaining panels by their sunlight hour values.
4. Reserving the places for LWS.

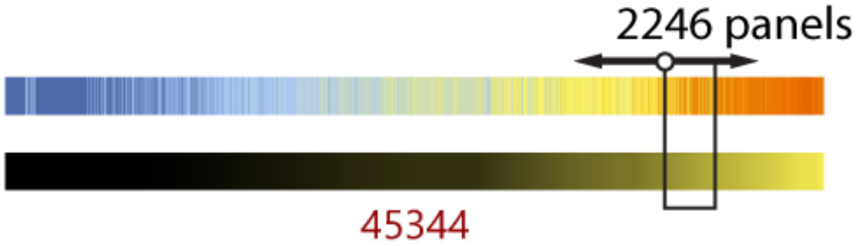


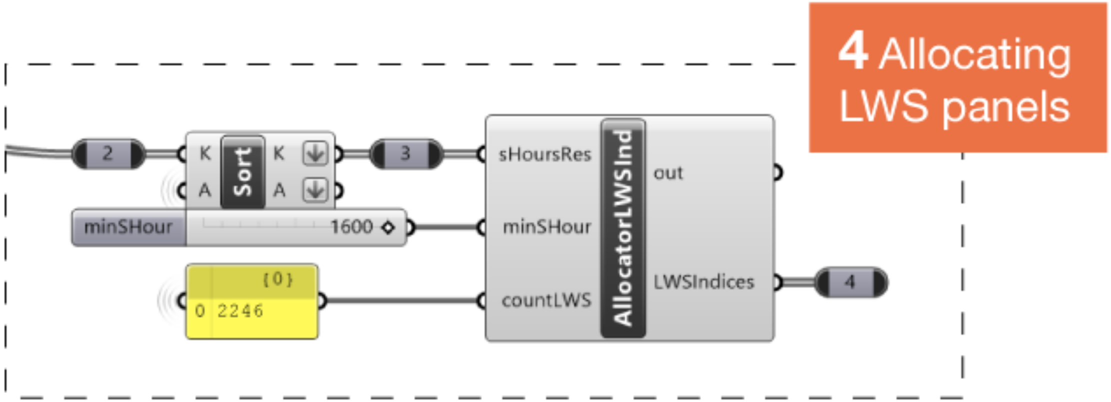


TU Delft

LWS
sunlight hours

LWS minimum sunlight hour can be selected for a range of panels allowing future revisions.

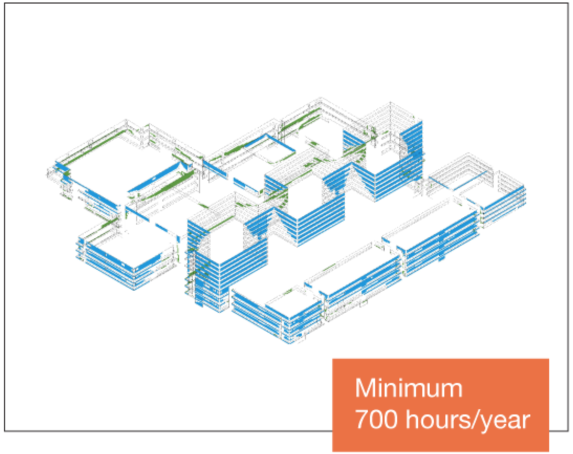


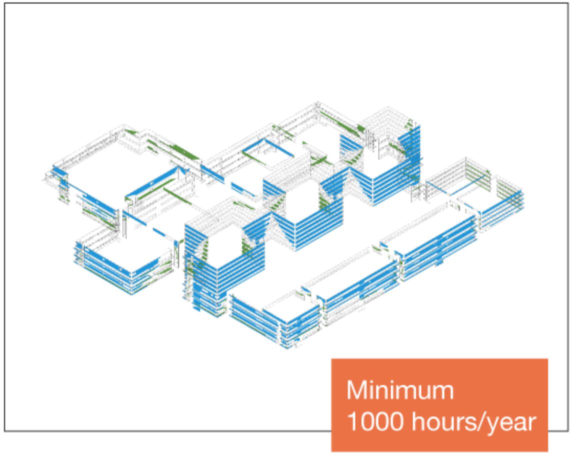


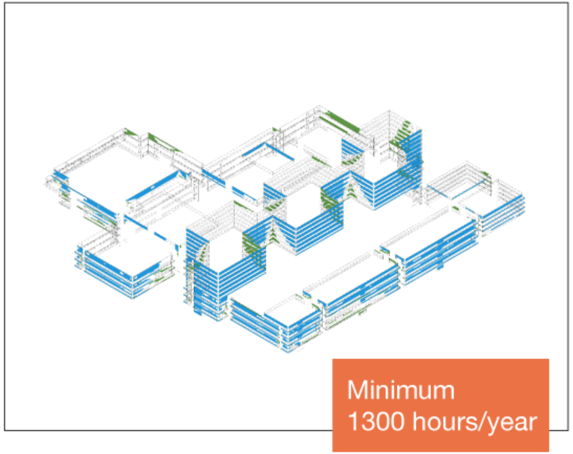
TU Delft

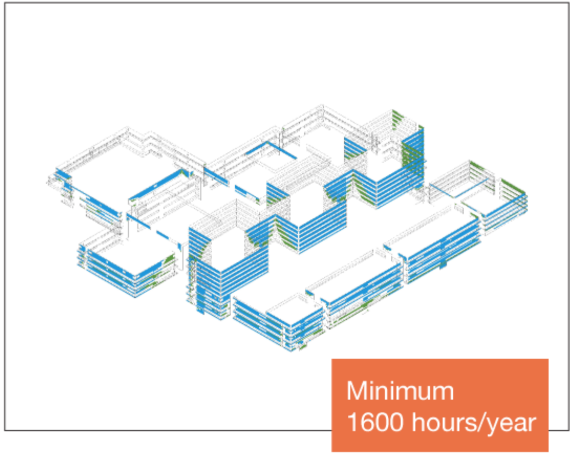
LWS sunlight hours

- Different species needs
- Reserving places for additional BIPV





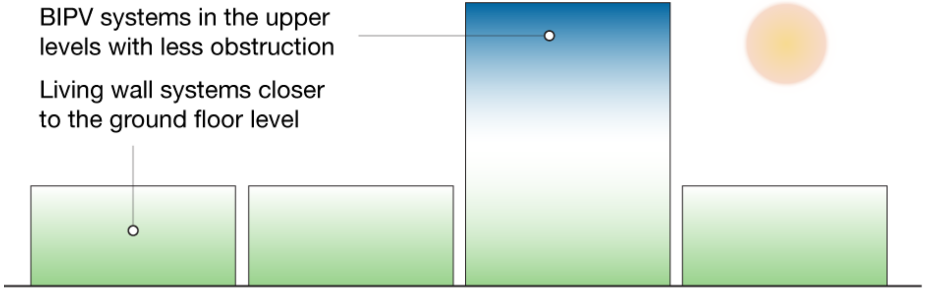


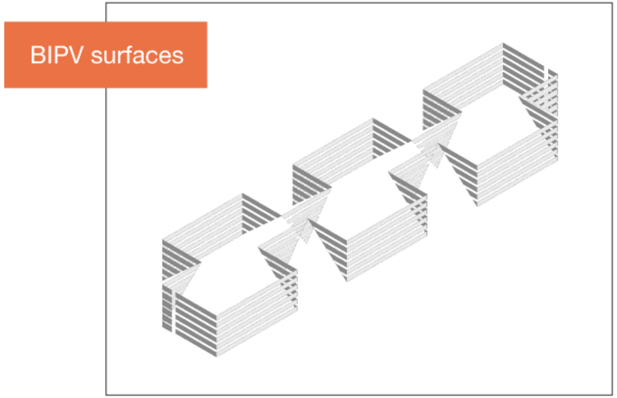


TU Delft

Design assessment using the toolkit

- Quick façade panelling
- Determine cash flows during the project lifetime and make financial assessment
- Affordability of other parts of the project by the BIPV system

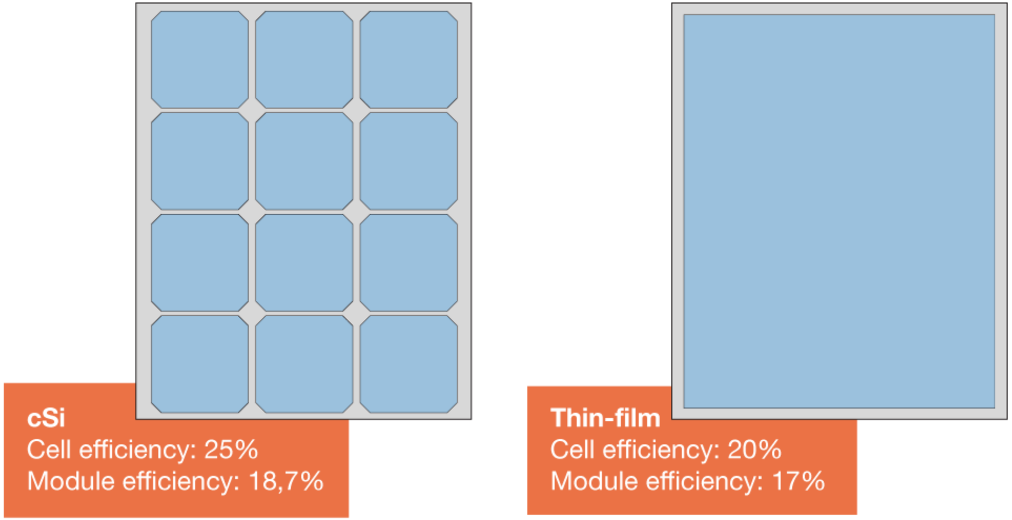




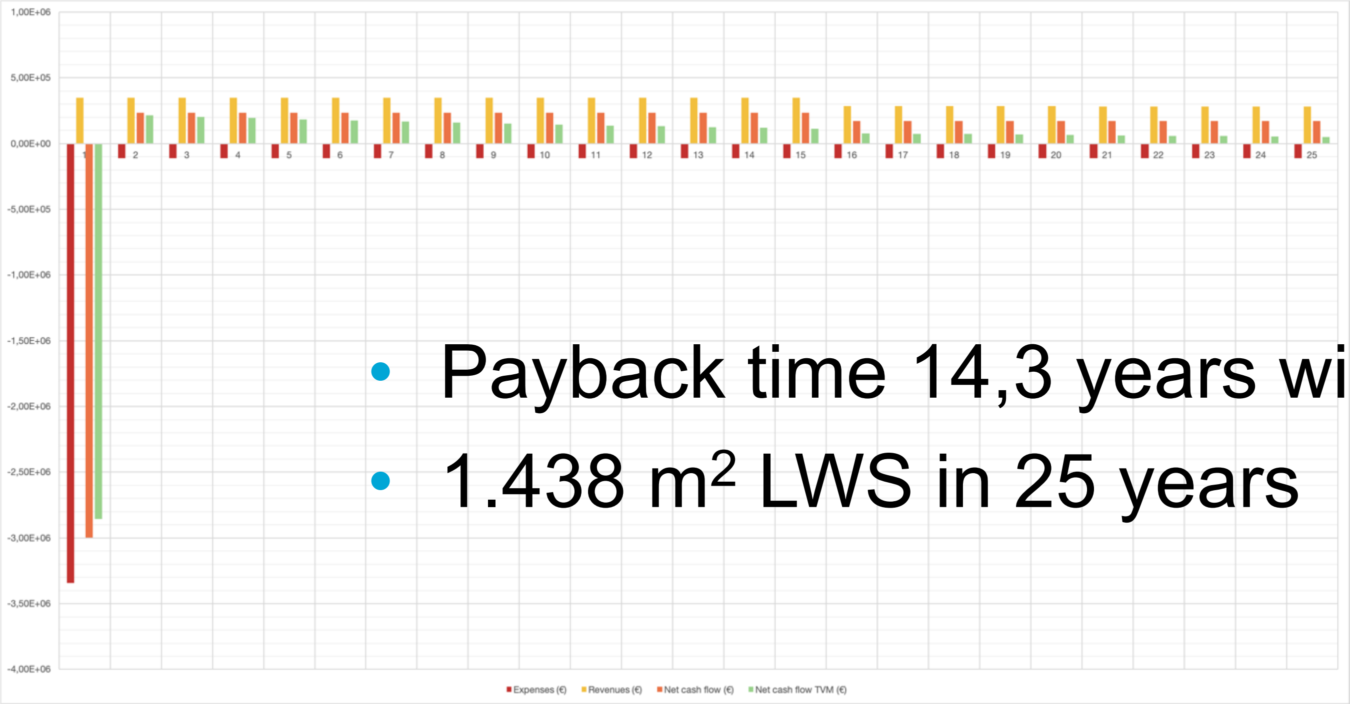
TU Delft

Optimising panel dimensions

- Panels 64 cm by 57 cm (Galapagos)
- 93 per cent covered
- c-Si or thin-film PV?



Financial assessment



- Payback time 14,3 years with only BIPV
- 1.438 m^2 LWS in 25 years

TU Delft

Conclusions

- **How can the cost-effectivity of an early-stage BIPV design be assessed and optimised computationally within the frame of the AMC case?**
- We developed a computational toolkit can be used for the financial assessment of a given design and generate optimum early-stage design solutions integrating BIPV and LWS technologies.

Conclusions (continued)

AMC low-rise and high-rise building façades need thermal improvement. We elaborated on how the improvement can be done and applying BIPV may be a suitable time for it. With all the opaque surfaces covered with PV, 5 per cent of the annual demand can be covered.

A façade system with easy panel replacement and making use of interchangeable panels, would make the system adapt to the building's changing needs.

By customising the BIPV panels, façade coverage can be increased and thus the investor can make more use of the façades with better insolation. Tilting the panels may have a financial benefit depending on the panel price.

BIPV technologies used in the building would only cover a small portion of the total demand, but this revenue can be used for financing other environmentally-conscious systems like living wall systems.

The proposed methodology aims to find the best possible options by finding how many of each panel type to buy and their proper allocation. However, the computational workflow proposed does not constitute a final decision tool, as architectural design is a much more complex process. So, we call the generated options "potential designs".

TU Delft

Thank you